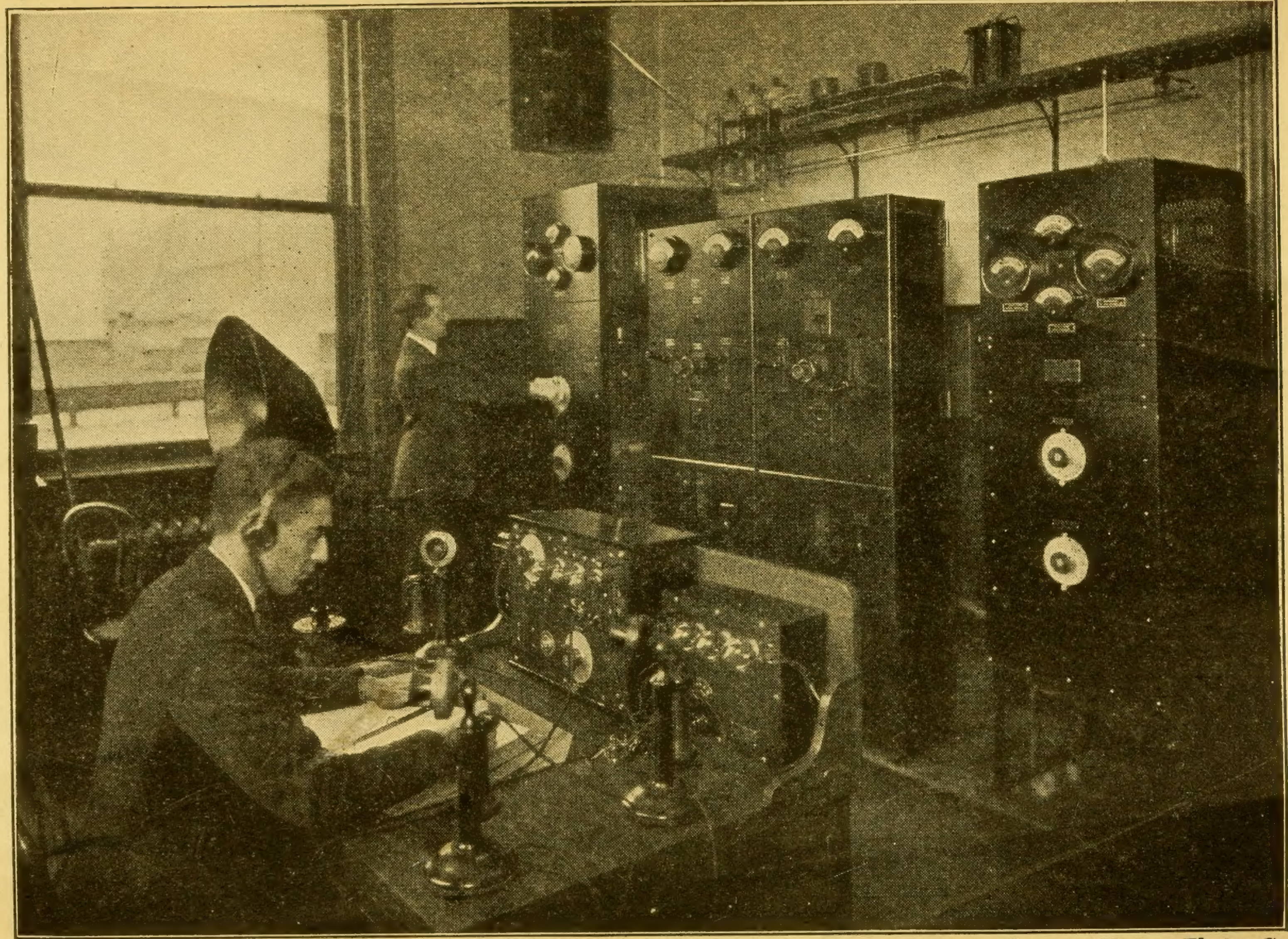

Courtesy Western Electric Co.

EQUIPMENT OF A BROADCASTING STATION.

The operator hears the program from the loud speaker on the desk and controls the strength of the outgoing waves. The sending sets are behind the panels at the right and left.

ELEMENTARY PRINCIPLES OF PHYSICS

BY

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PREFACE

The authors of *Elementary Principles of Physics* have long felt that students lose interest in Physics because of the formal presentation of the subject. There have been too many new terms, abstract concepts, and laborious calculations. The attempt has been made in this book to bring the subject to the student in language that he can readily understand and in steps which progress with his own mental development. This has been done without sacrifice of accuracy or completeness.

The student's *natural* interest in scientific phenomena is expressed by the questions: "What is it?" or "How did it happen?" Once he has answered these questions, he must next discover "Why does it happen?" Seldom does natural curiosity lead him to ask concerning measurements and mathematical relations the question: "How much?"

In this natural approach of the student to the subject lies the reason for the order of topics in this book, an order differing from the traditional one, which so often leads to loss of interest and to that feeling of dismay at difficult work too early in the course. The topics presented in the earlier part of the book are primarily observational and involve only simple relations and problems. The mechanics of solids, which when studied prematurely is likely to cause discouragement on account of its abstract and mathematical characteristics, is placed late in the book. Then the earlier experience with the science and some gain in

maturity will enable the student better to handle this difficult subject. For the same reason, the observational parts of light and heat are studied early and the quantitative relations later. In all these cases where subjects are divided, the earlier part presents the theory necessary for the basic explanations of the later parts. The order of topics has successfully stood the test of experience with a large number of classes. There is nothing in the treatment, however, to prevent teachers from using the chapters in the traditional order of topics.

The generally accepted physical theories may be very useful in unifying the knowledge of the subject, and in awakening the scientific imagination of the student. Consequently the elements of the kinetic theory are introduced in the second chapter and used throughout the study of fluids and heat. The wave theory, rather than ray constructions, is applied throughout the subject of light; and electrons are made the basis of static electricity and vacuum tubes.

The authors desire to call attention to certain outstanding features of the book:

(1) A large number of demonstration experiments, selected after years of experience on the grounds of simplicity and effectiveness, and designed to clarify and enrich the student's acquaintance with physical phenomena;

(2) Numerous fact questions placed at intervals in the chapters to enable the student to test his knowledge while studying the lesson of the day rather than merely to furnish him time-consuming written home-work;

(3) Abundant exercises at the end of each chapter, selected to emphasize the facts of the chapter, to encourage reasoning from these facts, and to give practice in the solution of such problems as come within the scope of the chapter;

(4) Summaries at the end of each chapter with keywords and formulas in bold-faced type, designed for both short-range and long-range reviews:

(5) A wealth of illustrations closely related to the text and planned to be of real help to the student; clear line drawings to furnish models for his own sketches, and half-tones to visualize for him the principles and the many practical applications of Physics.

Following the thirty-two chapters covering the topics of the usual first course in Physics, there are additional chapters treating special material of wide general interest and importance. These chapters deal with such subjects as the Automobile, Radio, Engines, Radium and Radioactivity, and Water Power, and should prove a valuable fund of material for the teacher who has more than the usual time allotment for the subject and to the student who desires to pursue topics that are of special interest to him.

The authors feel that Physics not only is fundamental among the sciences but is one of the most attractive, if properly presented to the student. They hope that this book will add fresh interest to the subject for teachers and that students reading its pages will realize the amazing range of physical phenomena interwoven in their everyday life and the strikingly simple and orderly set of principles that underlies all, and that thereby they may gain to some extent the scientific habit of thought.

R. W. F.
R. B. B.
D. L. B.

New York City,
April, 1924.

ACKNOWLEDGMENTS

The authors have been very generously assisted in securing timely illustrative material by many scientific men, manufacturers, and engineering companies, to whom they extend their hearty thanks. The source of each picture so furnished is indicated under the picture itself. Thanks for making drawings are due Mr. George Wright, Mr. Kerr C. Eby, Mr. Norman T. Shelton, Mr. W. K. Kleinecke, Mr. John C. Arnell, and Mr. Laurance H. Brownlee. Dr. G. Failla of the Radium Laboratory of the Memorial Hospital gave very helpful suggestions for the chapter on Radium and furnished the illustrations; Mr. Howard W. Mott, of Stuyvesant High School, assisted greatly in the work on Radio Communication, both in constructive criticism and in illustrative material; Mr. Clarence H. Sanford, of Stuyvesant High School, assisted in securing illustrative material on Engines. Others who have given generous assistance are: Dr. E. R. von Nardroff, Mr. Walworth K. Bradbury, E. Howard and Company, the United States Coast and Geodetic Survey, the Carnegie Institution, the Mount Wilson Observatory, Mr. Robert C. Brownlee, and Mr. Alexander Efron.

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ELEMENTARY PRINCIPLES OF PHYSICS

CHAPTER I

MATTER AND FORCE

1. Matter. — The world is full of things that we can see and feel. Our houses and the furniture in them, the earth we walk on, the water we drink, bathe in, and sail on, the air

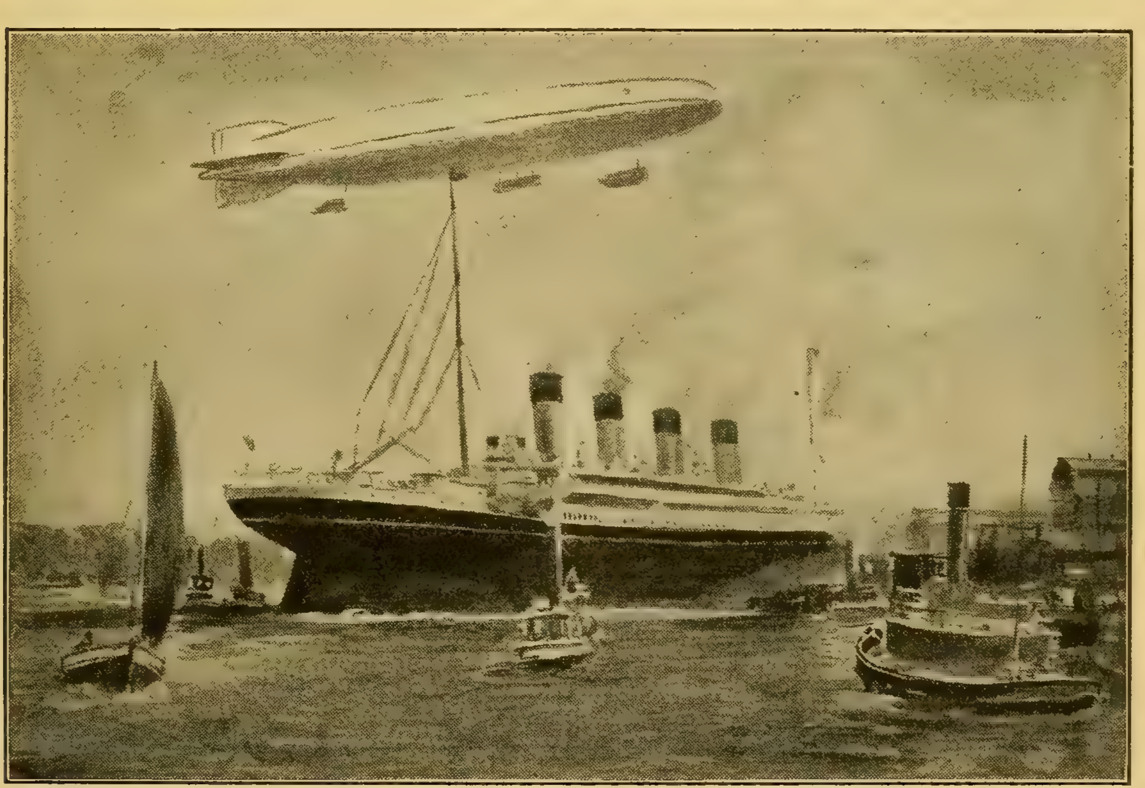


FIGURE 1. — LAND, SEA, AND AIR.

The boats and land are solid matter; the water is liquid matter; the air, the steam, and the helium in the dirigible are gaseous matter.

that we breathe and that blows over us, are things whose existence we are sure of, because each makes some impression

on one or more of our senses. All of these things are composed of *matter.*

Different kinds of matter are called *substances.* A *body* is a definite piece of matter, large or small. The sun and a grain of sand are both bodies, for each consists of a definite amount of matter, that is, it has a definite *mass.* For the present, we will define *matter* as *anything that takes up space.*

2. Impenetrability. — We can drive a nail into wood, because the fibers on either side of the nail are compressed to make way for it. We cannot drive a nail into iron, because no such compression takes place. The nail and the wood do not occupy the same place *at the same time. The inability of two bodies to occupy the same space at the same time is called the impenetrability of matter.*

FIGURE 2. — IMPENETRABILITY.

EXPERIMENT 1. — Impenetrability may be illustrated by an experiment with the apparatus shown in Figure 2. With the pinchcock closed, water is poured into the funnel. A little water enters the bottle, because air is compressible. *Why does not all the water run down?* When the pinchcock is opened, the water does run down. *What becomes of the air that was in the bottle?*

3. Inertia. — Things tend to remain as they are. When the steam is shut off in a locomotive drawing a train over a level track, the train runs for a considerable distance before various resistances bring it to a stop. A ball on a polished table, over which it can be rolled with the greatest ease, does not begin to move unless some force starts it. Both of these cases illustrate the property of *inertia. Inertia is the tendency of bodies in motion to remain in motion and of bodies at rest to remain at rest.* Inertia is a universal property of matter.

It furnishes the explanation of why we fall forward if we jump from a moving train; of why an automobile skids when a corner is turned rapidly; and of countless other happenings in our daily life. The turning of the earth on its axis with speed that is undiminished, because it meets no resistance to this motion, is another example of the tendency of a body in motion to remain in motion.

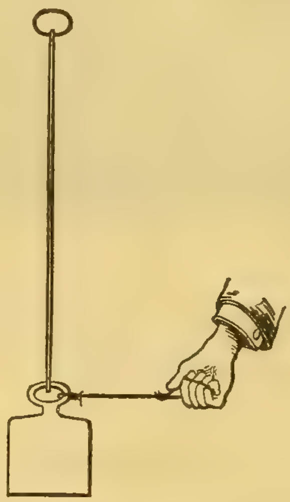


FIGURE 3. — INERTIA OF REST.

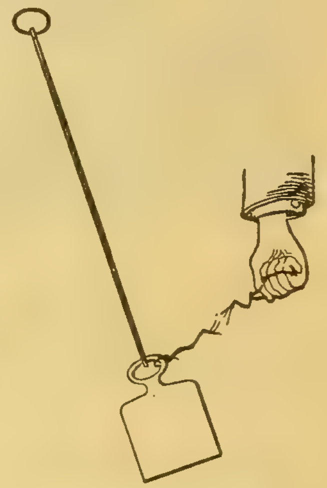


FIGURE 4. — INERTIA OF MOTION.

EXPERIMENT 2. — Suspend a heavy weight by a strong cord or rope (Figure 3). Attach a piece of ordinary twine to this weight, give a sudden pull to the string, and observe the result. Again attach the twine, and by gentle pulls, timed with the natural swing of the weight, again set it in motion. When the weight is swinging through a considerable arc, try to stop it by holding fast to the end of the string (Figure 4). *Show that the result in each case illustrates the inertia of the body.*

4. States of Matter. — In Arctic regions, water is obtained by melting ice. If the ice water thus formed is heated sufficiently, it turns into steam. The ice, the water, and the steam are the same substance in different *states*. Ice is an example of the *solid* state, water of the *liquid* state, and steam of the *gaseous* state. A solid retains a definite form and has a definite volume. A liquid takes the form of the vessel containing it and fills a definite part of it. A gas has no form whatever, but fills the vessel to which it is admitted. A gas, therefore, unlike a solid or a liquid, does not have a definite volume. The internal structure of the different states of matter and the reasons for their characteristic properties will be taken up in the next chapter.

FIGURE 5. — THE FORCE OF WIND.

The constant force and direction of the wind on this mountain top has fixed the form of the tree.

5. Force.—Whenever we wish to overcome the inertia of a body, we give it a push or a pull. These words describe the application of a *force* from us or toward us respectively. We become conscious of the idea of force through the action of our muscles in moving bodies or in opposing their motion. *Force is that which changes or tends to change a body's state of motion or of rest.*

Courtesy of Bureau of Standards.

FIGURE 6. — STANDARD KILOGRAM.

This weight is kept at the Bureau of Standards, Washington. It is made of nearly unalterable platinum and iridium, yet protected from the action of the air by two glass covers, as seen at the left. The picture also shows the covers removed and the tongs used to place the weight on a balance.

Forces are at work around us all the time. The forces of winds (Figure 5) and waves, of engines and machines, are familiar examples. *Weight* is the force of attraction between

a body and the earth. The amount of this attraction for a certain definite mass of metal, which we call a "weight," furnishes the most convenient standard for measuring other forces. Such definite weights have been prepared by each government (Figure 6). Common units of force, therefore, are pounds, ounces, grams, kilograms, etc. There are two convenient methods of comparing and measuring forces, one depending on the elasticity of springs and the other on a direct comparison of the pull of the earth on masses of known and unknown weight.

QUESTIONS

1. Why does the water rise in a kettle when potatoes are put in it? Give another household application of the same principle.

2. What use is made of inertia by a coal shoveler? By a wood chopper?

3. What could you learn about inertia by starting to run and by trying to stop running on smooth ice?

4. What relation has inertia to many automobile accidents?

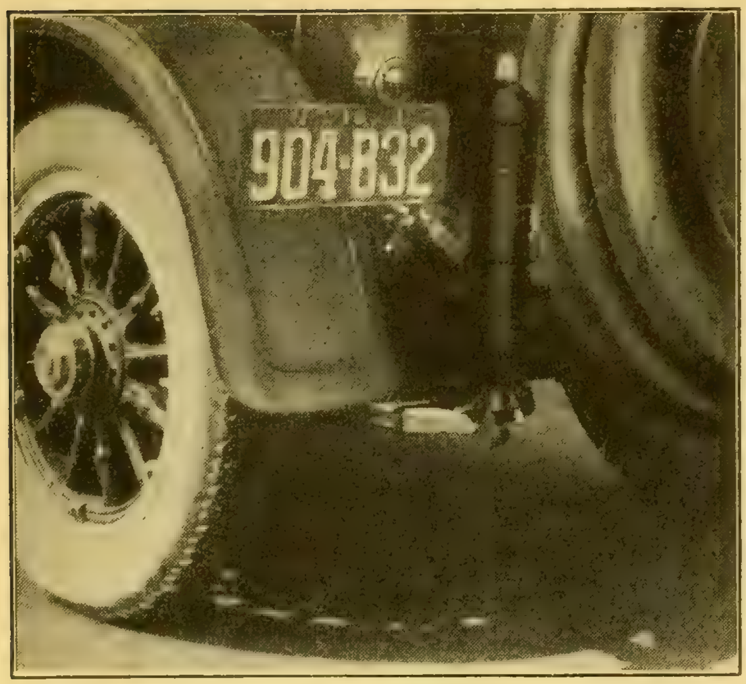
5. Name two common substances other than water that may exist in different states at different temperatures.

6. Name two differences between the solid and the liquid state.

7. Against what force are tall buildings, signboards, barns, and similar structures braced?

8. What force makes the climbing of hills difficult? Possible?

6. Elasticity. — When a solid rubber ball is compressed by striking the pavement, it regains its original form, and the force with which it does so causes it to rebound. A steel spring that has been stretched moderately regains its original length when the stretching force is removed. The ball and the spring are *elastic* bodies; so are glass marbles and ivory billiard balls. Wet clay and dough, on the other hand, are *plastic*, retaining any form that is given them by moderate pressure. The line between elastic and plastic bodies is not definite. Even plastic materials have a slight elasticity.



Courtesy of Westinghouse Air Spring Co.

FIGURE 7. — ELASTICITY GIVES COMFORT.

Passengers are protected from shocks by the elasticity of the steel springs, of the air and rubber in the tires, and by the "air springs."

Elasticity is the tendency of a substance to regain its original form or volume, when the external force that deformed it is removed. The elasticity of solids is that of form.

7. The Spring Balance. —

EXPERIMENT 3. — Suspend a coiled spring, with a pan and pointer at the lower end, so that the pointer may be opposite a meter stick or other vertical scale (Figure 9). Put weights of 100, 200, 300, 400, and 500 grams successively into the pan, and note in each case the amount the spring is stretched, as indicated by the pointer and scale. *How do the amounts of stretching produced by different weights compare? See if you can make a proportion between two of the weights and the elongation produced by them.*

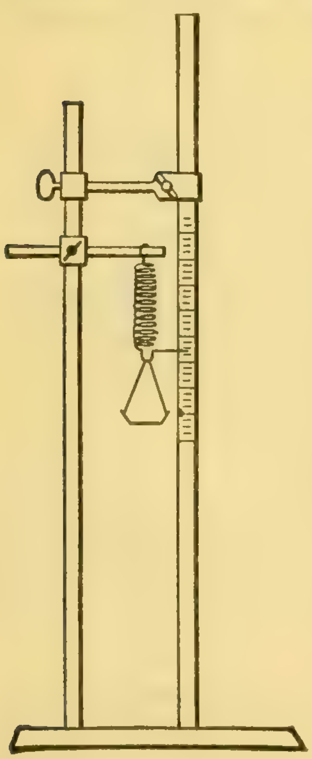
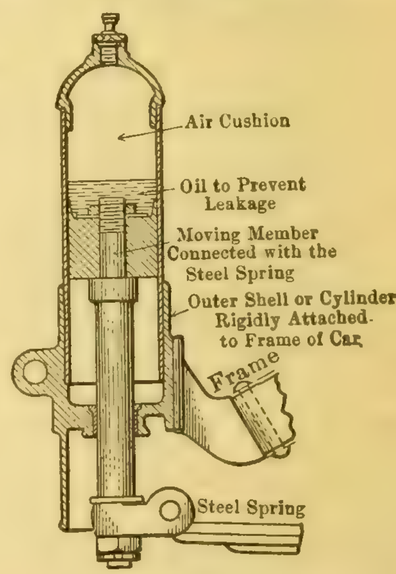


FIGURE 9. — HOOKE'S LAW.

This experiment illustrates the principle which is applied in the spring balance (Figure 10).



Courtesy Westinghouse Air Spring Co.

FIGURE 8. — AIR SPRING.

Bumps cause the piston to compress the air, and its elasticity protects the passenger.

In this case the pointer moves over a scale surrounding the spring. If you examine the graduations on the scale of such a balance, you will notice that they are evenly spaced. A 5-pound weight stretches the spring a certain distance, a 10-pound weight stretches it twice as far. Since each pound of weight stretches the spring a definite amount, the spring balance may be used to measure any force in terms of the units of weight in which its scale is marked.

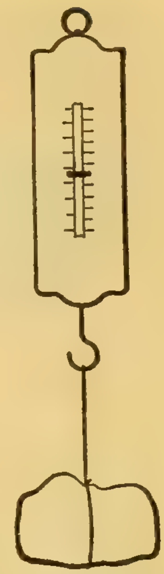
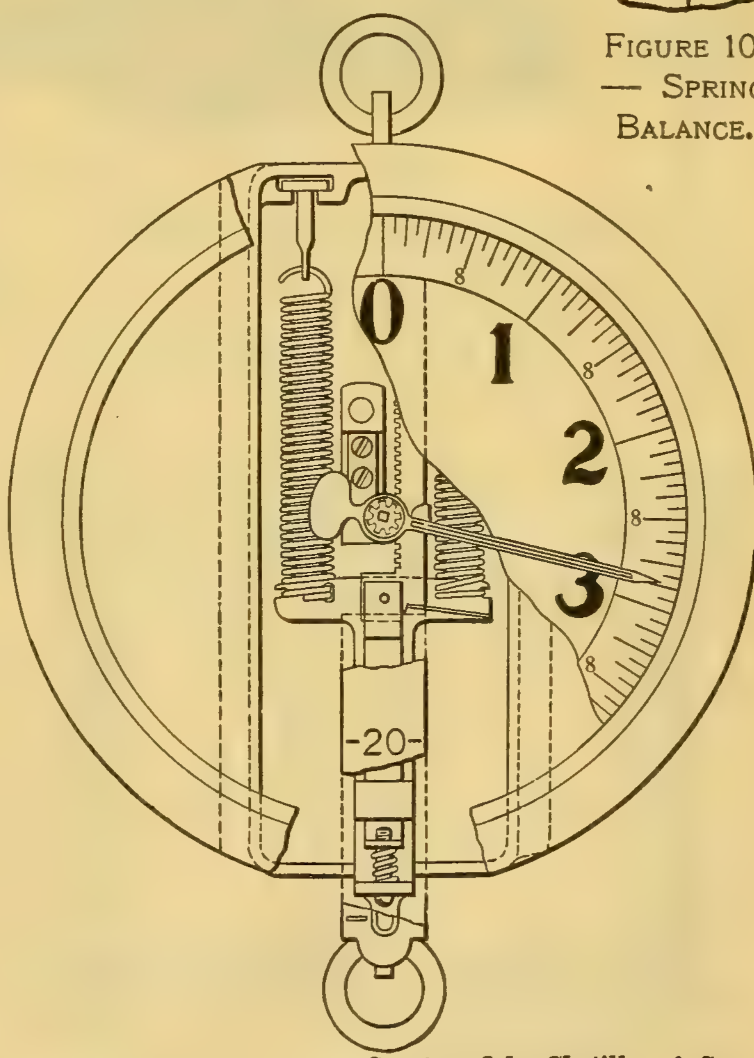


FIGURE 10. — SPRING BALANCE.

When spring balances are thus used, they are often called "dynamometers," which means "force measurers." By the proper selection of size and material, spring balances may be adapted to the measurement of forces all the way from those in delicate experiments to the force with which a locomotive pulls a train.



Courtesy John Chatillon & Sons.

FIGURE 11. — BUTCHERS' SCALE.

Two springs are used and their small motions are magnified by the toothed rack moving the pinion, which turns the pointer over the large dial.

8. Elastic Limit and Hooke's Law. — A rubber band that has been

stretched too much does not completely regain its original length. The same thing is true of a steel spring. Solids

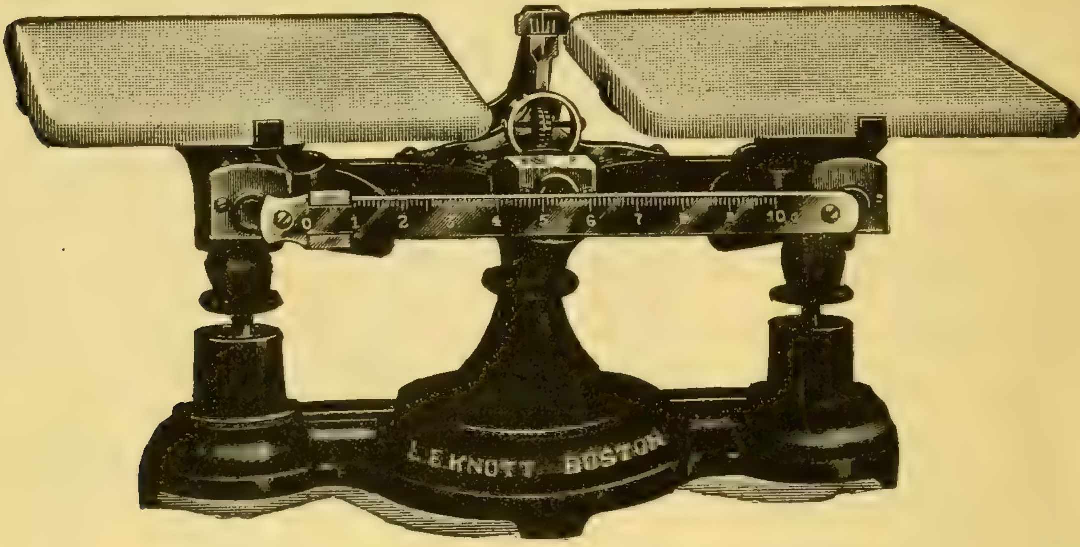


FIGURE 12.—PLATFORM BALANCE.

are never perfectly elastic after too great a force has been applied. For each body there is a maximum force that can be applied and still permit the body to regain its original shape completely. This force is called the *elastic limit* of that body. If a greater force is applied, a permanent change in form takes place. In making spring balances, care is taken to have the highest reading well below the elastic limit of the spring.

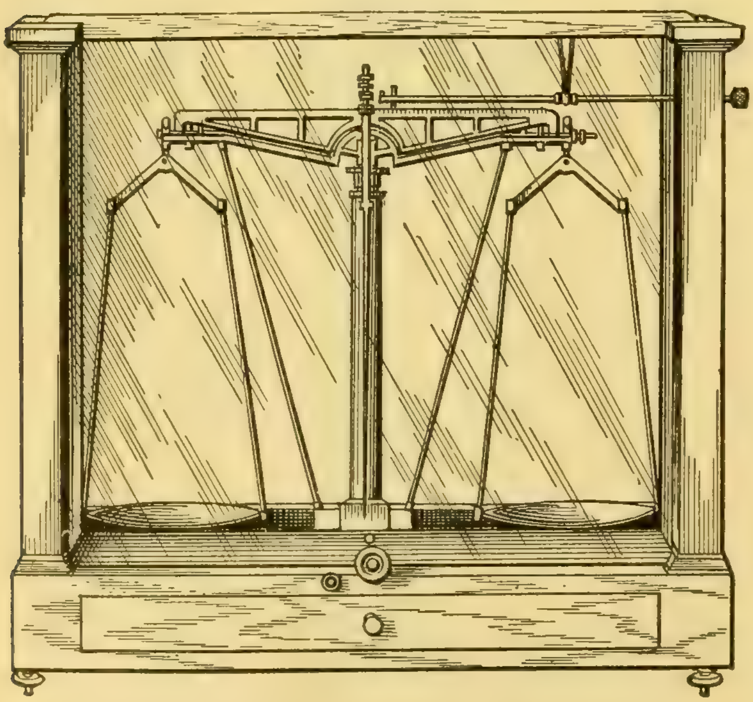


FIGURE 13.—CHEMICAL BALANCE.

Balances of this type may be made so sensitive that a single hair will cause the pan to descend.

The relation be-

tween the force applied to a spring and the change produced by this force was first stated by Robert Hooke. Hooke's Law states: The amount of change in the shape of an elastic body is proportional to the force applied, provided that the elastic limit is not exceeded. If we call the applied force the *stress*, and the change in shape the *strain*, we may say that the *strain is directly proportional to the stress.*

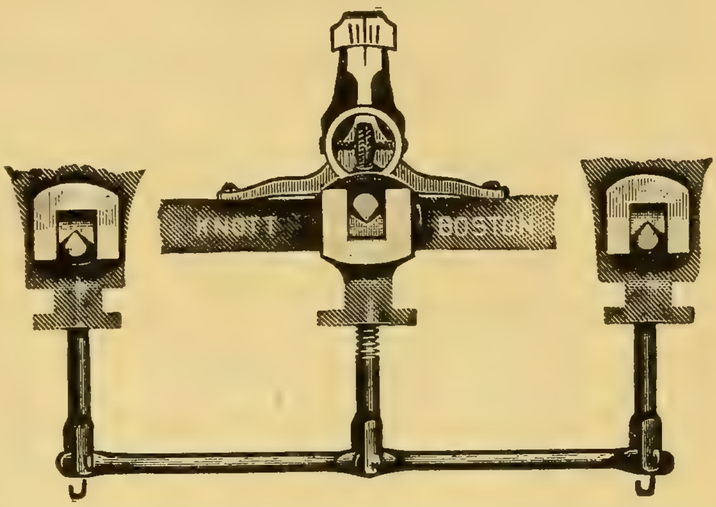


FIGURE 14.—SECTIONAL VIEW OF BALANCE.

The hardened steel knife-edge at the center is the fulcrum, and each pan rests on a knife edge.

9. The Balance. — The method of direct comparison of weights is used in the platform balance (Figure 12) and the beam balance (Figure 13). In these balances two scale pans of equal weight are supported at equal distances from a common support or *fulcrum* (Figure 14), about which they can easily turn. There is the same pull between each pan and the earth. That is, they are "balanced" or in equilibrium. If additional weights are placed on one pan, that pan moves down because of this additional weight. If then we place on one pan an unknown weight, to restore the balance we may add known weights to the other until the pans are just even. The force due to the unknown weight is then equal to that due to the known weight, and we have found the amount of the unknown weight. Forces other than weights can be measured by this means, but usually not as conveniently as by a spring balance.

SUMMARY

Matter is anything that takes up space. **Substances** are different kinds of matter. **Bodies** are definite pieces of matter. **Mass** is the quantity of matter in a body.

Impenetrability is the inability of two bodies to occupy the same space at the same time.

Inertia is the tendency of bodies at rest to remain at rest and of bodies in motion to remain in motion.

Matter exists in solid, liquid, and gaseous states. **Solids** have definite form and volume. **Liquids** have definite volume, but take the form of the containing vessel. **Gases** have neither definite volume nor form.

Force is that which changes or tends to change the state of rest or motion of a body. Forces act as pushes or pulls.

Elasticity is the tendency of a substance to regain its original form or volume, when the external force that has deformed it is removed. **Hooke's Law** states that the strain is directly proportional to the stress. The spring balance applies this law. Forces are measured by the use of either spring or beam balances. These balances compare the forces with known weights, and compare masses by comparing the earth's attraction for them.

EXERCISES

1. Name five different kinds of matter. State whether each is solid, liquid, or gaseous at ordinary temperature.

2. Define impenetrability. Why does the water in a tub rise when you get into it?

3. Why is it harder to start an automobile than to keep it running? Why are brakes necessary to stop a train?

4. Explain why beating removes dust from a carpet. Why is it dangerous to face backward when getting off a moving car?

5. Give three other applications of the inertia of moving bodies and three of the inertia of stationary bodies.

6. Give ten practical illustrations of applying force.

7. Name four units used in measuring force.

8. Name two devices used in the measurement of forces and explain the operation of each.

9. Name four elastic bodies not mentioned in the text, and state in each case how you know the body is elastic.

10. Name two plastic substances, and explain how you know each is plastic.

11. What is the elastic material used in a football? Has this material elasticity of form or of volume?

12. State Hooke's Law and describe an experiment to show it.

13. Explain the meaning of *stress, strain*, and *elastic limit.*

14. What change takes place in the elasticity of rubber with age? Illustrate.

15. How may a rubber band be made to exceed its elastic limit?

16. Why are different size springs used for screen doors and wooden doors?

17. Why cannot the door of a closet be slammed shut?

18. How is elasticity made use of in the automobile? In playing tennis? In the air rifle?

19. Explain the action of the "air spring."

20. Are elastic or inelastic rigid bodies more easily broken? Give examples.

21. In a true balance, why could you interchange the article to be weighed and the standard weight and still maintain equilibrium? Would this be true for a balance with unequal arms?

CHAPTER II

MOLECULES AND THEIR BEHAVIOR

10. Constitution of Matter. — The behavior of matter is what we study in Physics. In order to account for the behavior of different kinds of matter, a theory of the make-up of matter has been reasoned out and accepted by scientific men. According to this theory, each body is made up of a

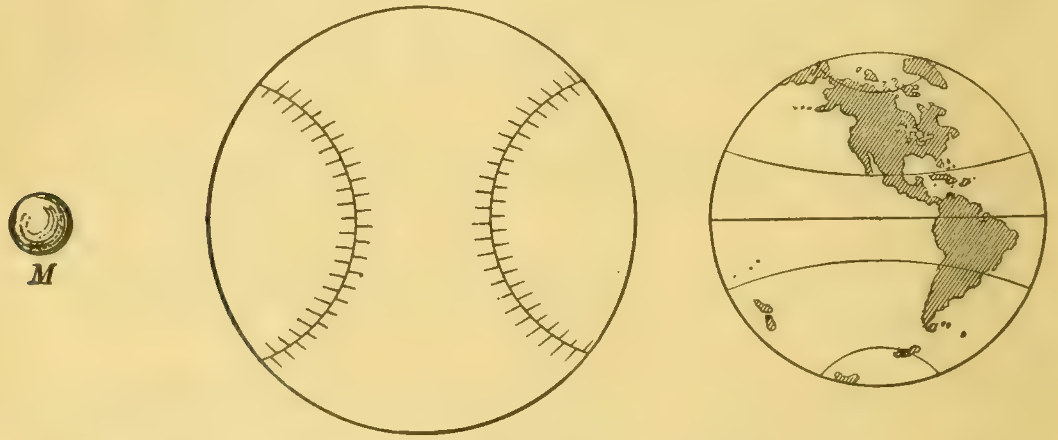


FIGURE 15. — SIZE OF MOLECULES.

If we could magnify a molecule of water until it was as large as *M*, a baseball on the same scale would be larger than the earth actually is.

vast number of tiny particles, called *molecules*. The average diameter of gas molecules is calculated to be about one three-hundred-millionth of an inch (Figure 15). There are as many kinds of molecules as there are elements and compounds. Elements are the simplest forms of matter, while compounds are substances composed of elements. In Physics we are not concerned with the composition, formation, or decomposition of molecules; these subjects are studied by the chemist.

We believe in the theory that matter consists of molecules, because this theory explains the behavior of matter more simply and more completely than any other yet proposed. *A molecule is the smallest particle of a substance that has the properties of the substance.*

11. Motion of Molecules. — All molecules are in constant motion, as will be explained more fully in the chapters on

FIGURE 16. — ACROPOLIS AT ATHENS.

These buildings have been standing for 2300 years.

Heat. The molecules in gases move more freely than do those of liquids and solids; molecules in liquids move more freely than molecules in solids. Hence changing a body from one of these states to another consists in altering the amount of freedom of motion of its molecules.

12. Cohesion and Adhesion. — Buildings are standing to-day that were built thousands of years ago (Figure 16). There must be forces holding their molecules together, even though these molecules have a very limited motion. When

grains of powdered graphite are pressed together with great force, solid blocks are formed, from which pencil leads are made. *The force that holds molecules of the same kind together*

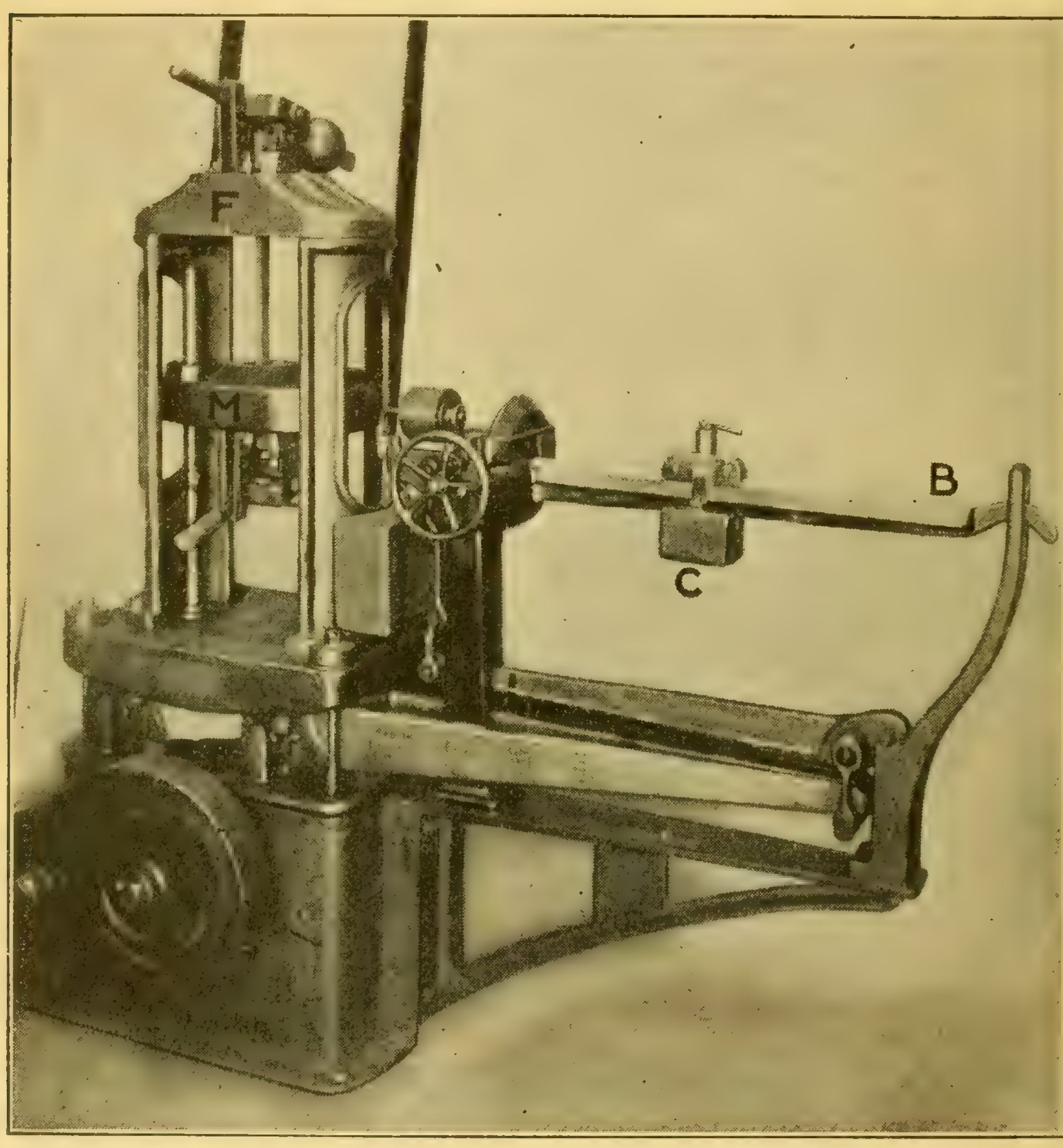


FIGURE 17. — TESTING MACHINE.

Force is applied to the specimen gripped between the fixed head (*F*) above and the movable head (*M*), which is pulled down by the two screws. The applied force is regulated and measured by the beam (*B*) and counterpoise (*C*.)

is called cohesion. Adhesion is the force that holds *unlike* molecules together. There is the same kind of force in both cases, a force of molecular attraction. Glue, mucilage, mortar, and cement are called "adhesives," because the

force of adhesion to other substances is particularly noticeable in them. Cohesion and adhesion act only if the molecules are very near each other; this accounts for the fact that chalk sticks to the blackboard and pencil marks adhere to paper.

Molecular Forces in Solids

13. Tenacity. — It requires a force of 60,000 pounds or more to pull apart a bar of machine steel one inch square. *The resistance offered by a body to being pulled apart is called tenacity.* It is the measure of the cohesion of the molecules when subject to a pulling force.

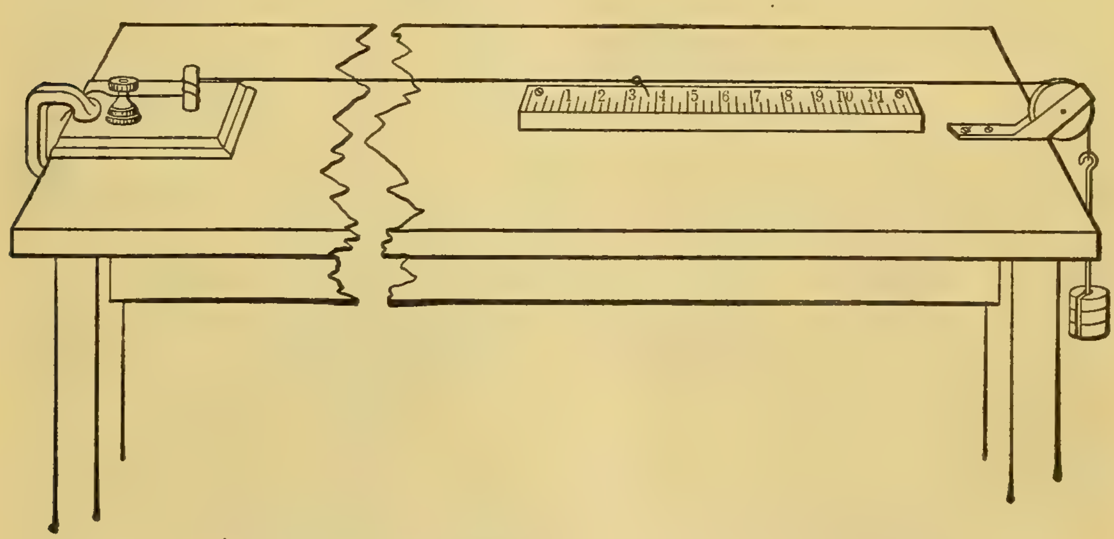


Figure 18. — Tensile Strength of Wire.

Experiment 4. — The tenacity of a metal may be measured by fastening one end of a piece of # 28 wire securely to a screw in the table top and exerting force on the other end, which passes over a pulley on the edge of the table, and is attached to a hanger on which weights are placed, until the wire breaks. The wire should be given two or three turns around a cylinder just in front of the screw (Figure 18). This cylinder prevents the wire from being cut.

Metals in general possess great tenacity, wrought iron, steel, brass, and phosphor bronze being particularly tenacious. Gold, tin, and lead have little tensile strength. Some special

steels have a tensile strength of over 100 tons per square inch. The use of cords and ropes depends on their flexibility and their tensile strength.

14. Ductility. — The process of making a wire consists of drawing a metal rod through a tapering hole in a steel die (Figure 19). The tenacity of the metal prevents breaking, if the difference in diameter of the two ends of the hole is not too great. As the wire is pulled through the die, the outer layer of molecules slips backward and inward, and the cohesion of the metal is sufficient to prevent them from being pulled off, and the wire from being pulled apart. Since the process forces the

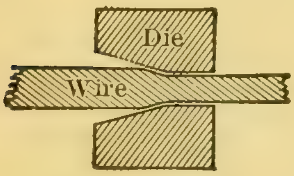


FIGURE 19.

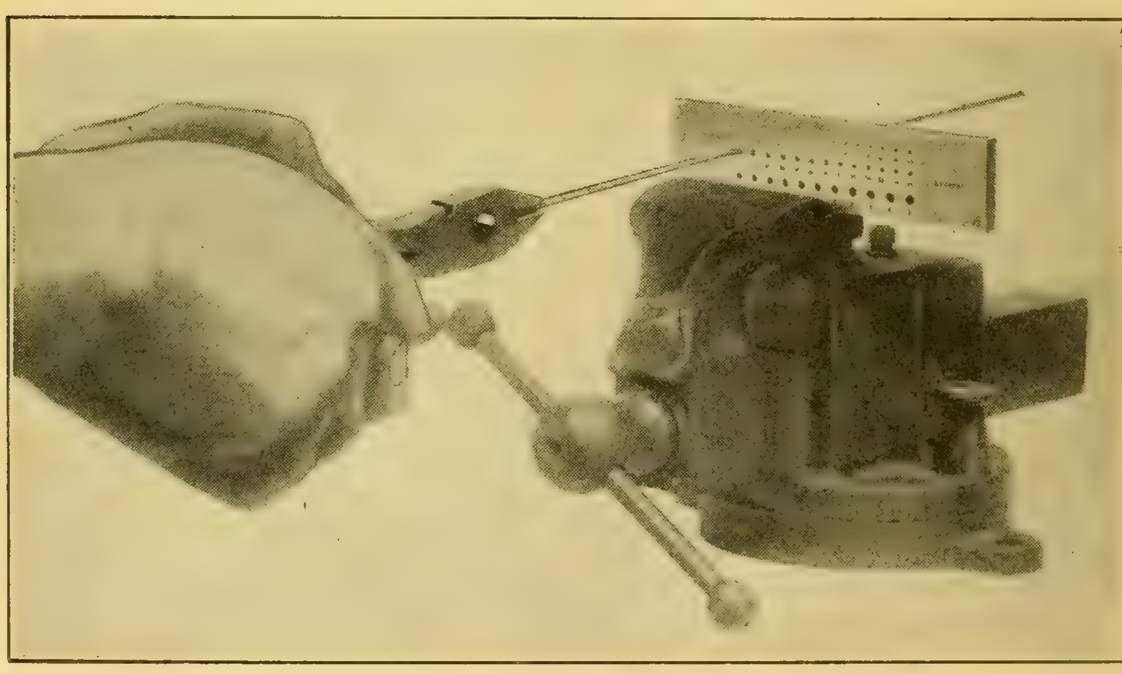


FIGURE 20. — A WIRE DRAWING PLATE IN USE.

The wire is drawn successively through smaller and smaller holes until the desired size is obtained. When necessary, the wire is annealed.

molecules nearer together, it increases both the tenacity and the hardness of the metal. *The capability of some substances to be drawn into wire is called ductility.*

The fineness of the smallest sized wire that can be drawn from a metal is the measure of its ductility. Platinum can be drawn by a special process into wire three hundred-thousandths of an inch in diameter. Silver, copper, iron, and gold are other exceedingly ductile metals.

15. Malleability. — Gold has been beaten into sheets so thin that it would take nearly 300,000 of them to make a

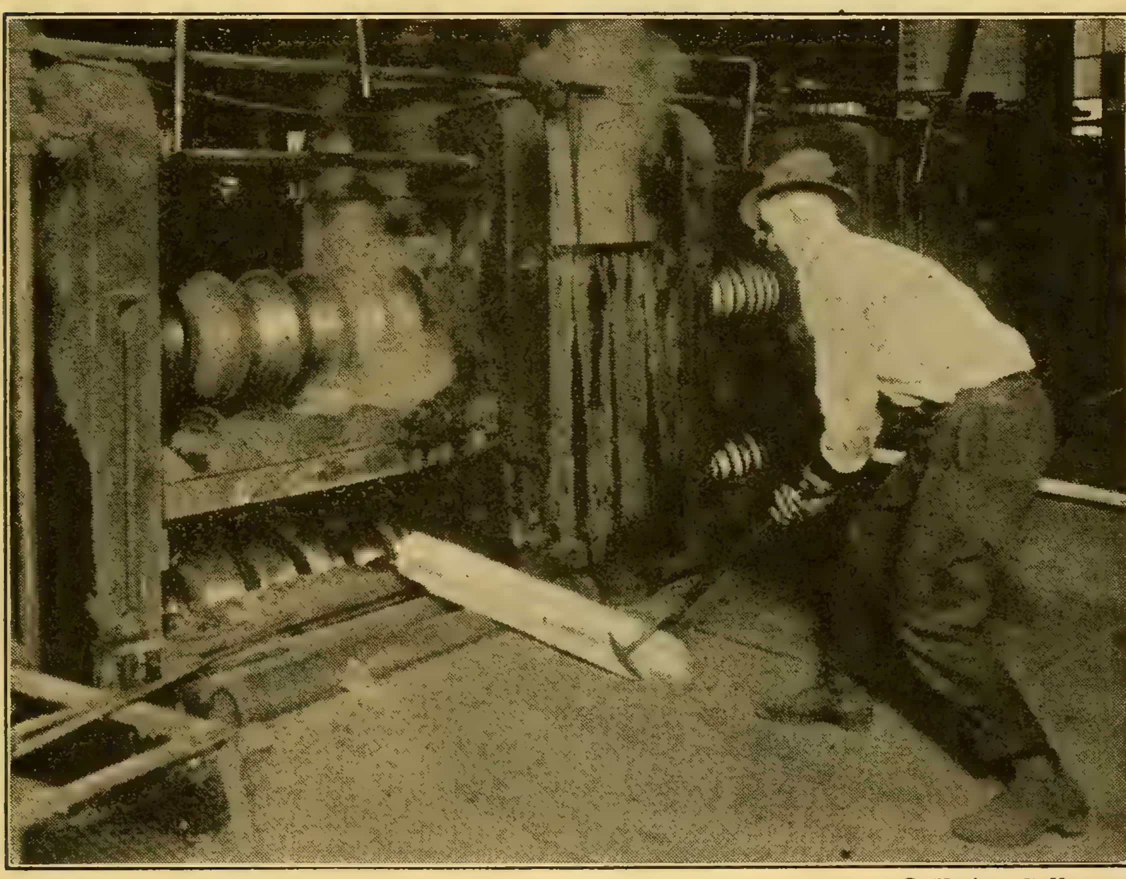


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FIGURE 21. — ROLLING MILL FOR STEEL.

The hot steel bar seen in front of the rolls is passed back and forth through grooves of decreasing size. Rails and steel forms are made in this way.

pile an inch high. The blacksmith hammers wrought iron into whatever shape he desires. Copper, lead, and tin can be made into thin sheets by passing them between rollers under great pressure. These are illustrations of *malleability* (Latin *malleus*, a mallet). *Malleability is the capability of some subtances to be hammered or rolled into thin sheets.* Both

ductile and malleable substances show some degree of plasticity (§ 6), because their molecules, when displaced by drawing or hammering, do not return to their former position.

16. Hardness. — A diamond scratches glass and steel. A sharp piece of copper will scratch lead. We say that the diamond is harder than glass; copper harder than lead. *The hardness of a body is the resistance of its molecules to being forced apart.*

FIGURE 22. — TEMPERING FURNACE.

The steel is heated white hot and hardened by plunging into the pail of water. When heated again, the color of the surface indicates the temperature at which it is to be chilled again to temper it.

The sudden cooling of a metal from a red or white heat often increases its hardness, notably so in the case of steel. Hard materials are often brittle, that is, they break easily when subjected to shock. Hardened steel is too brittle for use, and must be toughened by *tempering*. The steel is heated to a temperature below that at which it was hardened (Figure 22). It is then cooled slowly until the brittleness has been sufficiently reduced. The change is then stopped by suddenly plunging the steel into water. Tempering reduces the hardness as well as the brittleness of steel.

Glass is rendered less brittle by *annealing* it. This is done by a very slow cooling of the finished glass articles, such as bottles, window glass, tubing, etc.

QUESTIONS

1. What is a molecule? Compare solids, liquids, and gases as to the motion of their molecules.

2. Define cohesion. Name five substances in the order of their cohesive force.

3. Name four adhesives, and explain their action in terms of molecules.

4. Define ductility and malleability, and explain the relation of these terms to cohesion.

5. Name three metals of high tenacity; two of low tenacity.

6. What is the effect of wire drawing on the hardness and tenacity of the metal? Explain why this effect is produced.

7. How can the relative hardness of two materials be compared?

8. Describe how steel is (*a*) hardened, (*b*) tempered.

9. Name two practical processes that depend on malleability.

10. Name three materials in the order of their hardness. How is this order determined?

Molecular Forces in Liquids

17. Cohesion and Adhesion in Liquids. — The slightest breeze ruffles the surface of a quiet pool. The weight of a grain of sand let fall into the water forces the molecules of water apart and causes the sand to settle to the bottom. Yet a stone, when taken out of water, appears *wet;* that is, some water adheres to its surface. This fact shows the action of both *adhesion* and *cohesion.* The layer of molecules of water, in actual contact with the surface of the stone, adhere to it; the remaining molecules of water are held to this surface layer and to each other by cohesion (Figure 23).

Experiment 5. — Cement a loop of wire to a glass disk with sealing wax. Attach to the loop a spring made by winding 20 turns of small

FIGURE 23. — A WET STONE.

Greatly exaggerated molecules are indicated by the little circles, and the forces holding them to each other and to the stone are indicated by arrows.

piano wire around a cylinder an inch in diameter. By means of the spring, lower the disk upon the surface of clean water, and press the disk gently against the surface with the other hand, so that a good surface contact may be secured. Now pull up gently on the top of the spring, and note that it stretches considerably before the disk is pulled away from the water surface (Figure 24). When the disk does pull away from the water, it is seen to be wet. *What evidence have you of (a) adhesion between water and glass; (b) cohesion of water?*

Dry the disk thoroughly, and repeat the experiment with a dish of clean mercury. *In which case is the spring stretched more before the disk is pulled away? Is the disk dry or wet with mercury? Does this show that the adhesion of mercury and glass is greater or less than the cohesion of mercury? Which was greater in the case of water, adhesion or cohesion?*

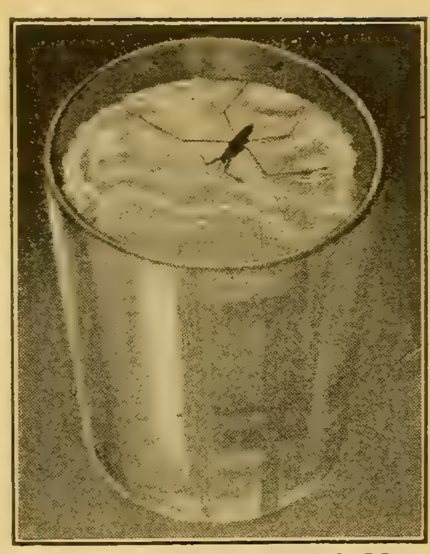
FIGURE 24.

18. Surface Films. — A safety razor blade, if carefully laid on the surface of water, will float, although it is more than seven times as dense as water (Figure 25). A needle may be floated in the same way. Black water beetles are seen skimming over the surface of ponds, without even their feet breaking through the top layer (Figure 26). In each of these

FIGURE 25. — FLOATING RAZOR BLADE AND NEEDLE.

They have been drawn together by surface tension. The bent wire is used to lay the needle on the water.

cases, close observation will show that the surface is slightly dented by the floating body (Figure 27), as if the water were covered with a membrane or film, on which the needle or the insect's feet are supported. If the needle penetrates the surface, it immediately sinks, because it displaces less than its own weight of water. The surface of a liquid on which the needle floats differs in some way from the interior through which it sinks.



Courtesy Pop. Sci. Mon.

FIGURE 26. — THE WATER BEETLE.

Surface tension keeps his feet from breaking through.

FIGURE 27. — The needle dents the surface, but is upheld by the cohesion of the surface molecules.

This difference is explained by the cohesional forces between the molecules of the liquid. If we consider a molecule far enough below the surface to be completely surrounded by other molecules, it will be pulled in all directions at once by these molecules with equal forces. The force in any one direction will be just balanced by an equal force in the opposite direction (Figure 28). But the molecules in the surface layer are attracted only by each other and by the molecules *below* them. This attraction crowds the molecules closer together at the surface, and so increases their cohesion. This makes the surface tend to contract like a stretched sheet of rubber.

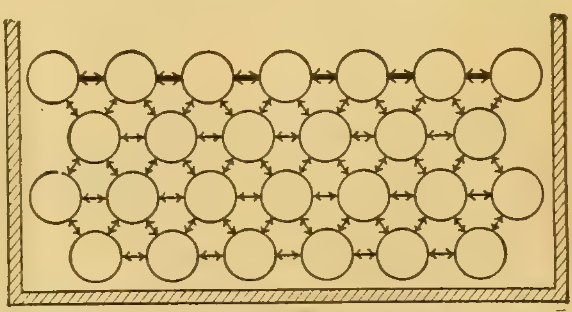


FIGURE 28. — MOLECULAR FORCE IN A LIQUID.

The arrows indicate the forces holding together the molecules, represented by circles.

19. Surface Tension. — *Surface tension is the name given to this tendency of a liquid surface to contract and become as small as possible.* Water in a vessel has only one free surface, so its surface tension does not ordinarily show itself. Heating a liquid reduces its surface tension. Adding to water a drop of another liquid that will mix with it usually reduces the surface tension of the water. Thus, two match sticks laid near each other on water will be seen to move apart if the water between them is touched with a hot wire, or if a drop of alcohol falls on the surface between them. The surface tension of gasoline is less than that of lubricating oil, or of a mixture of oil and gasoline. This fact is important in removing grease spots. The proper method is to pour the gasoline around the grease spot before pouring it on the spot. If the gasoline is poured into the center of the spot, the greater surface tension of the mixture of grease and gasoline will cause the greasy gasoline to draw away from the pure gasoline in the center, and a slight ring of grease surrounding the original spot will be left in the cloth.

20. Experiments in Surface Tension. — The results of the following experiments are explained on the basis of surface tension.

Experiment 6. — Pour a few drops of water on a clean glass plate, and allow the water to spread over the plate in a thin film. Let a drop of alcohol fall on the water near the center. *How does the surface tension account for the result?*

Experiment 7. — Cut a small boat out of the thin end of a shingle. Thrust a pin into the little boat, and using the pin as a handle, gently place the boat on clean water in a clean dish. Wet the stern of the boat with a little alcohol or ether. *Remembering that impurities lower the surface tension, account for the behavior of the boat.*

Experiment 8. — Shape a piece of fine-mesh copper gauze into a boat and solder the ends together. Carefully place the boat on a dish

of water. *Result?* Completely immerse the boat in water. When it has filled with water, release it. *Result?* *Why did it not sink at first?*

21. Drops. — It is a familiar fact that when a liquid is broken up into small bits, these become nearly or quite spherical drops. Shot is made by pouring melted lead through a sieve and allowing the drops to fall far enough to solidify. Glass marbles are made by heating the end of a glass rod until drops of molten glass fall. The contraction due to surface tension makes the drop spherical, because a sphere has less surface for a given volume than any other geometrical form.

FIGURE 29.

Large drops are not usually perfect spheres, because the weight of the liquid flattens them. The drops into which the mercury shatters, when it falls on the table, however, form nearly perfect spheres, because of the great surface tension of mercury.

EXPERIMENT 9. — Make a mixture of alcohol and water which has exactly the same density as olive oil. Into a flat-sided jar or bottle filled with this mixture, introduce 5 cm^3 of oil by means of a pipette. A large spherical drop of oil will be formed (Figure 29), because the weight of the oil is supported by the dilute alcohol and the surface tension of the oil is free to act.

22. Soap Bubbles. — Soap films have been of great use in studying surface tension, because the weight of the liquid used is so small and because there are two surfaces at which surface tension can act. As in the case of drops, the spherical form is due to surface tension. The action of this force can be readily seen if a bubble is allowed to remain on the bowl of the pipe, and a lighted match is placed before the opening in the end of the pipestem. The bubble contracts, squeezing out a stream of air that deflects the flame. If a

glass funnel is used in place of the pipe, the film will run from the mouth of the funnel to the stem.

FIGURE 30. — The two sides of the thread hang close together.

EXPERIMENT 10. — Bend a piece of wire into a ring about 2 inches in diameter, provided with a handle. Make a loop of thread about an inch long and suspend it in the wire ring. Dip the ring and loop into a dish of soap solution and draw it out in such a way as to leave a soap film across the ring (Figure 30). Thrust a hot wire into the film in the loop of thread. The soap film in the loop is broken and the loop drawn out into a circle (Figure 31). *Why?*

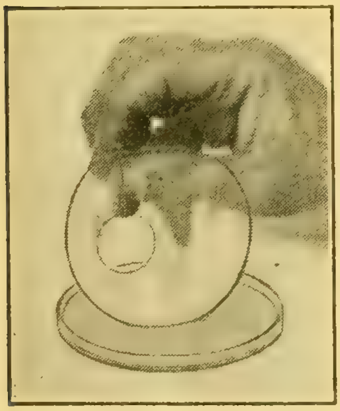


FIGURE 31. — The film is broken inside the loop.

EXPERIMENT 11. — A fork of #22 wire (Figure 32) is suspended from one side of a horn pan balance and carefully counterpoised. The fork prongs are plunged into a soap solution and the dish is then adjusted so that the flat top of the fork is about a centimeter above the liquid. As fine shot are dropped into the opposite pan of the balance, one at a time, the fork will rise, carrying a film of soap solution up with it. It will be found that the fork will rise some distance before the film breaks, and that considerable force has been necessary to overcome the tension of the film.

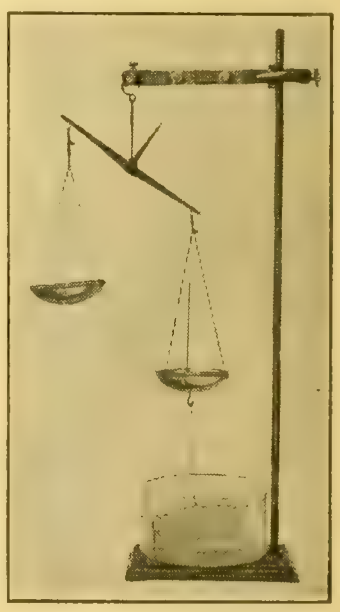


FIGURE 32. — The soap film is seen on the fork within the dish, holding the balance pan down.

23. Viscosity. — Alcohol and water flow rapidly when poured. Oil flows more sluggishly and molasses still more slowly. Evidently the molecules of alcohol slide over each other more readily than those of oil. There is more friction between the molecules developed in the flow of oil than there is in that of alcohol or water. *Viscosity is the name given to the*

molecular friction shown in the flow of liquids. In oils, the viscosity usually increases with the density. Thus, lubricating oil, which is denser than kerosene, is more viscous than

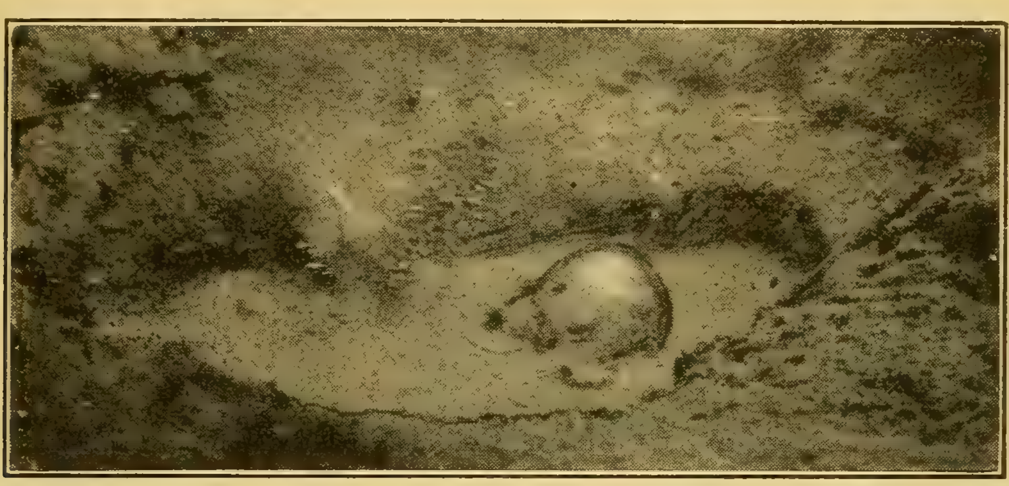


FIGURE 33.—A MUD BUBBLE.

Steam from beneath the surface of this mud pool in Yellowstone Park blows a bubble of mud before it escapes. The bubble is seen nearly ready to break. The bubble is large because of the viscosity of the mud.

kerosene. Although pure water has greater surface tension than soap solution, the latter is more viscous. So we can blow large bubbles with soapsuds, but not with water. Cream and white of egg possess considerable viscosity, therefore they can be "beaten" or "whipped."

The calming of waves by the use of oil depends on both surface tension and viscosity. The fact that water has greater tension causes the oil to spread over a very large surface in a very thin film. But this thin film has greater viscosity than the water, and so prevents the crests of the waves from being broken up into spray by the wind and converts them into smooth rollers. That a water surface does possess viscosity can be shown by immersing in water a sharpened wire shaped like a fish-hook, and then carefully drawing it upward. A tiny, steep-sided hill will appear before the wire breaks through the surface. This fact is utilized in the hook-gage (Figure 34), employed in exact measure-

ments of liquid levels. Surface viscosity is due to the closer crowding of the molecules of the surface layer.

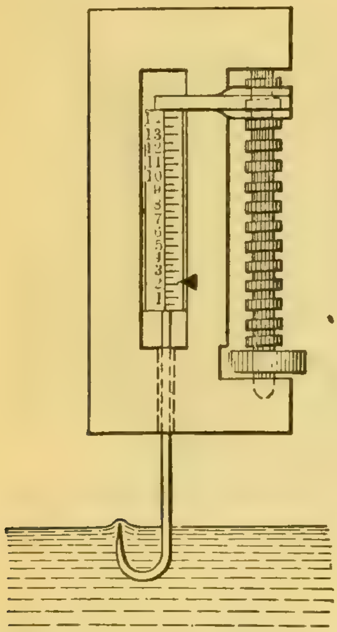


FIGURE 34. — HOOK-GAGE.

When the exact level is indicated by the "hill," the height of the liquid is measured on the scale.

Lubricating oils owe their usefulness to their viscosity, or "body." Kerosene would run out of a bearing, while machine oil or castor oil is retained between the bearing surfaces. The viscosity of oils decreases with the temperature. Very thick (viscous) oil is used to lubricate the piston of an engine, because an oil that would lubricate a bicycle bearing, where the temperature does not become high, would not have sufficient viscosity at the temperature of the engine cylinder. For bearings with heavy pressures or slow speeds, grease is used which the heat developed by friction will melt into a viscous oil.

The more viscous a liquid, the larger drops it will form in flowing through a given opening, and the longer the time it will take a given quantity to flow through the opening. The latter fact is used in comparing the viscosity of lubricating oils.

24. Capillary Action. — Oil rises in a lampwick; ink runs up into blotting paper; coffee runs up into a lump of sugar if a corner is held in the liquid. Other forces beside gravity must be acting here, for the liquids do not "seek their level." In every such case, the liquid rises in thin, hair-like tubes or narrow spaces. For this reason, these phenomena are known as capillary phenomena, from the Latin word *capillus*, a hair. The following simple experiments make an explanation of capillary action possible.

EXPERIMENT 12. — Into a beaker of clean water dip a capillary tube of glass. Immediately the water rises in the tube (Figure 35). Into a beaker of mercury dip another glass tube; the mercury is depressed in the tube below the level in the beaker. Moreover, the water surface in the capillary tube and the water surfaces where they touch the beaker, and the outside of the tube are concave. The corresponding mercury surfaces are convex.

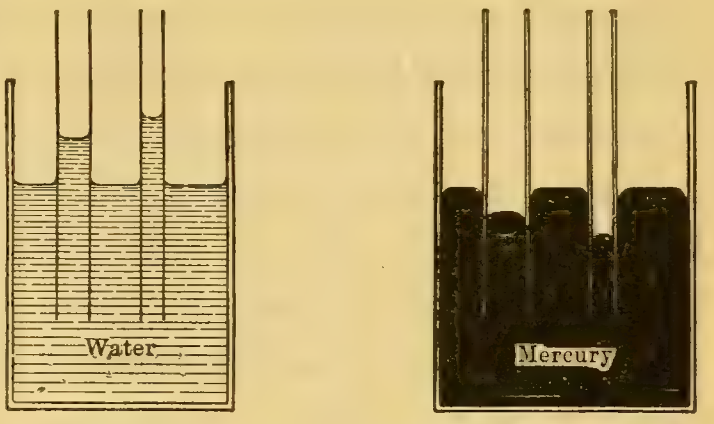


FIGURE 35. — CAPILLARY TUBES.
Note the shape, position, and relative heights of the liquids in each case.

25. Explanation of Capillary Action. — We have already (§ 17) seen that the adhesion between water and glass is greater than the cohesion of water. This means that the attraction between water and glass is greater than the attraction between water molecules. Where the water touches the glass the excess of attraction between the water and glass results in a pulling upward of the water on the surface of the glass. The glass molecules cannot be pulled toward the water, so the more easily moving water molecules are drawn upward by the glass.

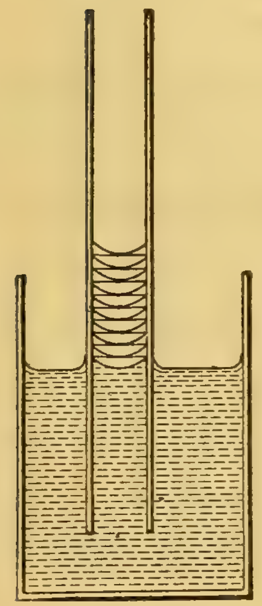


FIGURE 36. — The curved and straight lines show successive steps in the rise of the liquid.

Inside the glass tube the water rises to form a concave surface. The surface tension of the film then tends to straighten the surface. This causes the water level at the center of the tube to be raised a little above the level outside the tube. Then at the inner surface of the tube the water is again pulled up into a concave curve at the glass, and the surface

tension again straightens it (Figure 36). This alternate climbing at the edges and subsequent straightening of the liquid surface in the tube continues until the weight of the column of water lifted just equals the surface tension.

The depression of the mercury surface is accounted for in a similar way. The cohesion of mercury is greater than the adhesion between mercury and glass. Therefore the *contact curve* of mercury with glass is *convex* instead of concave. Surface tension flattens this convex curve and the column of mercury is forced downward until the upward liquid pressure on the column in the tube just equals the surface tension.

26. Laws of Capillary Action. —

I. *Liquids rise in capillary tubes which they wet; liquids are depressed in capillary tubes which they do not wet.*

II. *The amount of elevation or depression of a liquid is inversely proportional to the diameter of the tube.*

III. *The amount of elevation or depression decreases as the temperature rises.*

The first law is illustrated by the difference between the behavior of ordinary cotton batting and that of absorbent cotton. There are capillary spaces between the threads in both cases. In ordinary cotton there is fatty matter on the threads which prevents water from wetting them. The fat has been removed from absorbent cotton ; the fibers are wet by water and water will enter the irregular capillary spaces between the fibers.

The second law can be easily illustrated by inserting tubes of different diameter into the same liquid (Figure 35).

The effect of temperature is due to the lessening of the surface tension as the temperature rises.

27. Applications of Capillarity. — Capillarity has a great number of practical applications. Towels, sponges, and mops owe their usefulness to capillarity. When oil is supplied through an oil hole to a bearing, the oil wets the metal and is drawn into the space between the shaft and its bearing by capillary action. In soldering a tightly fitting joint, the surfaces are first freed from grease and oxides by a soldering fluid. Then a drop of solder, heated until it is very fluid, is placed on the hot joint; capillary action causes the solder to enter the narrow space, making the joint tight and firm when the solder hardens.

Capillary action is of great importance in supplying water to the roots of plants. It prevents the rain from sinking to great depths in the soil, and draws moisture from underground veins of water toward the surface. If capillary action were not checked in the surface layers of the soil, the moisture of the ground would all be brought to the surface and evaporated in dry weather. So the important operation of "dry farming" consists in keeping the surface layer of soil broken up to such an extent that the spaces between the lumps of earth shall be too large for capillary action.

QUESTIONS

1. Describe experiments to show the adhesion of mercury and of water to glass. Give comparative results.

2. Describe an experiment to show that the cohesion of liquids is greatest at the surface.

3. Name two liquids whose surface tensions are different and describe a practical application of this fact.

4. Describe the flotation of razor blades. What animals make use of this principle?

5. Why does a soap bubble on the end of a pipe contract when the pipe is withdrawn from the mouth?

6. Why is viscosity greater at the surface of liquids than within them?

7. What is meant by the term "contact curve"? Show contact curves of water with clean glass; water with greasy glass; mercury with zinc.

8. Make four drawings to show the positions of water and of mercury in large and in small tubes.

9. Explain the results shown in Question 8.

10. Define capillarity, and give two examples of its action.

11. State three laws of capillary tubes and illustrate each.

Molecular Forces in Gas

28. Motion of Gas Molecules. — As we have proceeded from solids to liquids, we have seen a great increase in the freedom of motion of the molecules, and a lessening of the forces of cohesion. In gases, the cohesive force is practically absent. Each molecule moves with great speed until it strikes another molecule, when it bounds off with undiminished velocity. In hydrogen, at 32° F, the molecules have an average velocity of more than a mile a second. Heavier molecules move more slowly, but the speed of all gaseous molecules is enormous. Heating the gas increases this speed; cooling the gas slows down the molecules.

29. Pressure of Confined Air. — The air that has been pumped into an automobile tire from the atmosphere, where it exerted a pressure of 15 lbs/in^2, may attain a pressure against the inner walls of the tube of 75 lbs/in^2. The pressure of this confined air is caused by the constant striking of the molecules of air against the walls of the inner tube (Figure 37). We have seen that air molecules move with the speed of a rifle bullet. A rain of bullets from a machine gun will batter down an obstruction of considerable strength. In a similar way the billions of molecules that are constantly

striking each square inch of the inner tube of the tire will have the same effect as that of a force of many pounds constantly applied, and so may cause a "blowout" if the tube is weak.

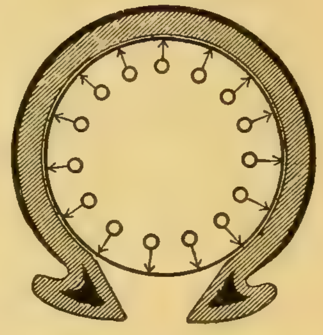


FIGURE 37.—A few greatly magnified molecules are shown striking the tire and so exerting pressure.

When a bottle that is full of air at ordinary pressure is corked, the molecules of air keep up the same motion that they had when it was open. They are striking each other and bombarding the walls, just as in the case of the air in the tire. Since there are fewer molecules in the bottle than in the tire, the blows are fewer, but the air exerts the same pressure that it did before being confined. So when any body of gas is confined, the pressure of the inclosed gas remains equal to the pressure put on the gas when it was confined, provided that there is no change in temperature. Compressed air in the airbrake shows this, since it exerts the same pressure on the brake as was used in compressing it.

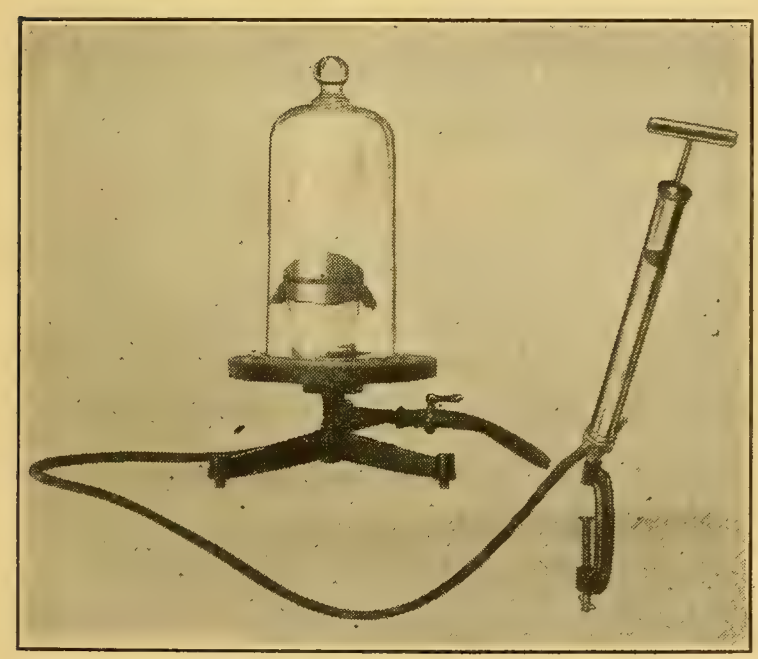


FIGURE 38. — PRESSURE OF CONFINED AIR.

The rubber membrane is forced outward by the bombardment of the molecules of air within the tumbler, when some of the air is removed from the jar outside.

EXPERIMENT 13. — Dip the mouth of an inverted tumbler into a dish of soap solution. On raising the tumbler, a soap film will be found across the top. *Is this film subject to any gas pressures? Why is it flat?*

Place the tumbler, with the film unbroken, on the plate of an air-pump, cover it with a bell jar, and pump out a little air from the bell jar. *What happens to the soap film? Why?*

Thin sheet rubber may be tied over the top of the tumbler, instead of using the soap solution (Figure 38).

30. Diffusion. — When a bunch of lilacs is brought into a room, or a bottle of chlorine is opened in a chemical laboratory, the odor is soon noticed across the room. Gaseous molecules, bounding back and forth, among the molecules of the air, have finally reached the nerves of the nose. This is an example of *diffusion.* Diffusion is not confined to gases, but shows itself in liquids, as in the sweetening of a cup of coffee by a lump of sugar dropped to the bottom of the cup. The uniformity of solutions is due to the diffusion of the dissolved particles. Diffusion takes place in spite of differences in density of the diffusing fluids. Diffusion often takes a long time, however, because of the constant collision of the molecules with each other, resulting in a very irregular path for each molecule (Figure 39). *Diffusion is the gradual mixing of the molecules of gases or liquids, without the application of external force.*

FIGURE 39. — PATH OF A GAS MOLECULE.

The points indicate collisions. Between collisions, the path is straight.

QUESTIONS

1. Describe, in some detail, the action of the molecules of a gas.

2. Explain how gases exert pressure against the walls of the containing vessel.

3. Describe and explain the experiment with tumbler and soap film.

4. Describe an application of compressed air that you have seen.

5. What is diffusion? Give two illustrations, one of the diffusion of gases and the other of the diffusion of liquids.

SUMMARY

A molecule is the smallest particle of a substance that has the properties of the substance. All molecules are in constant motion, those of gases moving most freely and those of solids least freely.

Cohesion is the attraction between **like** molecules; **adhesion** between **unlike** molecules. These forces are of a similar nature and act only at very short distances.

Tenacity is the resistance offered by a body to being pulled apart.

Ductility is the ability of some substances to be drawn into wire.

Malleability is the ability of some substances to be hammered or rolled into thin sheets. **Hardness** is the resistance of the molecules of a body to being forced apart. Tempering and annealing reduce the hardness of bodies.

Liquids show cohesion between their own molecules and adhesion to the surfaces of solids touching the liquids. If the **adhesion** between liquid and solid **is greater** than the cohesion of the liquid molecules, the liquid **wets** the solid. If the **cohesion is greater,** the solid **is not wet.**

The **surface layer** of liquid molecules (*a*) shows greater cohesion (viscosity) than the interior; (*b*) acts like a stretched film.

Surface tension is the force tending to make the surface of a liquid contract. This accounts for the formation of drops and for the behavior of soap bubbles.

Viscosity is the molecular friction shown in the flow of liquids. Oil is more viscous than water. The size of drops and the rate of flow through openings depend on viscosity.

Capillary tubes are tubes of very small internal diameter. The action of liquids in capillary tubes depends upon cohesion of the liquid molecules, adhesion between liquid and tube, and surface tension.

Laws of Capillary Action.

1. Liquids rise in capillary tubes which they wet; liquids are depressed in capillary tubes which they do not wet.

2. The amount of elevation or depression is inversely proportional to the diameter of the tube.

3. The amount of elevation or depression decreases as the temperature rises.

In gases, cohesion is practically absent, and the molecules are in very rapid motion. The **pressure** of a confined gas is due to the bombardment of the walls of the container by the gas molecules.

Diffusion is the gradual mixing of the molecules of gases or liquids, without the application of external force.

EXERCISES

1. Why does a piece of wood break when bent too far?

2. Why cannot the wood be mended by pushing the broken ends together, while two pieces of lead can be made to stick together by pressure?

3. Compare ice, water, and steam as to the motion of their molecules and the cohesion between them.

4. Why are the cables of suspension bridges made of steel wire?

5. What two properties of matter are illustrated in making a steel rail and how is each involved?

6. Give five examples, one of them a useful one, of the tendency of liquids to form spheres.

7. Explain the calming of waves by oil.

8. Why is oil used as a lubricant? How does it get into the bearings?

9. What is the reason for using lubricating oils of different grades of viscosity?

10. State and explain five *useful* illustrations of capillarity, taking one illustration from the household, one from agriculture, one from botany, and the other two from any source.

11. Explain why the air in an automobile tire sustains the weight of the car.

12. Why may compressed air, pumped into a compartment of a ship which has begun to leak, keep the water out?

13. A battery jar is half filled with blue copper sulphate solution, and less dense zinc sulphate solution placed on top. Where will a blue color be seen a month later and why?

14. Much more pressure is required to force a liquid through a long pipe than through a short pipe. How do you account for this?

15. Complete the following statements:

(*a*) Without ——, everthing would crumble to dust.

(*b*) Gas engines require oil of greater —— than sewing machines.

(*c*) The use of paper towels depends on ——.

(*d*) When a lump of sugar is put in coffee, it soon becomes sweet throughout because of ——.

CHAPTER III

PRESSURE OF LIQUIDS

31. Pressure Due to Gravity. — The water above the piston in a common water-pump exerts a pressure on the piston which must be overcome if the water is to be lifted. In a similar way, a pressure due to the weight of the water acts on the bottom of any tank or reservoir containing water (Figure 40). This pressure, due to the weight of a liquid, is called *gravity pressure.* If the reservoir has vertical sides, the combined weight of all the particles of water constitutes the *total gravity force* of the liquid against the bottom.

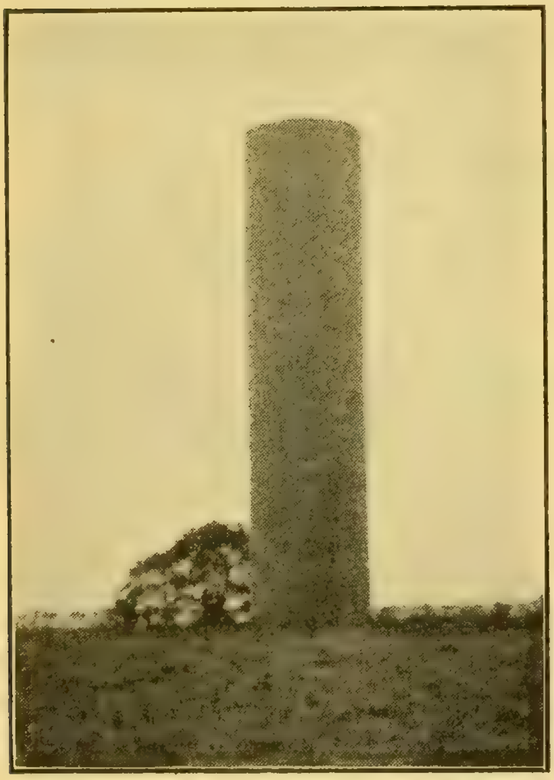


FIGURE 40. — A WATER TOWER.

The water in this tall tank exerts great pressure on the bottom.

The term "fluid" applies to both liquids and gases, since the particles of both move freely. Because all fluids have weight, they therefore always exert gravity pressure.

32. Units of Fluid Pressure. — People often speak incorrectly of steam pressure as 125 lbs; of the pressure of the atmosphere as 15 lbs; of water pressure at a faucet as 75 lbs. These are the pressures shown by pressure gages (Figures

41, 42). These pressures would be correctly stated if it were said that steam exerts a pressure of 125 lbs per square inch (lbs/in²); the air a pressure of 15 lbs/in²; and the water a pressure of 75 lbs/in². Pressure should always be expressed in units like pounds per square inch; pounds per square foot; or, in metric units, grams or kilograms per square centimeter. In each case the amount of *force on a unit area* should be stated. Nor should the term "pressure" be used when the total liquid force against a surface is meant; this should be called "total pressure," or better, "total force."

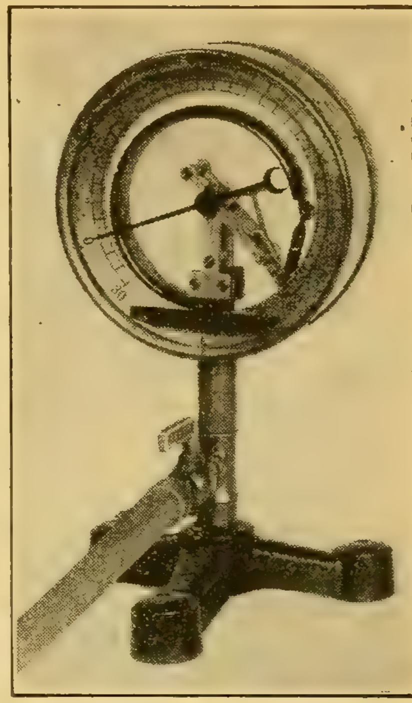


FIGURE 41. — A PRESSURE GAGE.

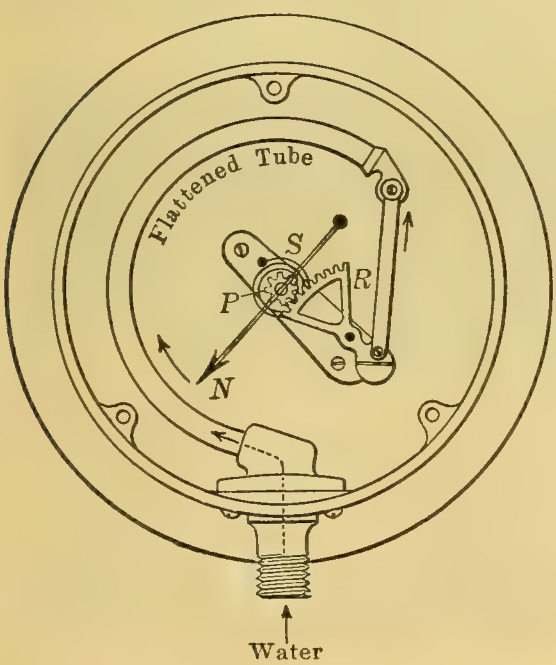


FIGURE 42. — The pressure of the fluid entering the flattened tube causes it to straighten upward. The rack R turns the pinion P, and makes the pointer N move over the scale. S is a hair-spring.

33. Factors Determining Gravity Pressure. — A cubic foot of water weighs 62.5 pounds, no matter what the shape of the vessel in which it is weighed. The pull of gravity on all the particles results in the downward force on the bottom of the containing vessel. If a cubic foot of water is poured into a narrow cylinder (Figure 43), such as a vertical pipe, the pressure per square inch on the bottom will be greater than if the water is put in a shallow pan.

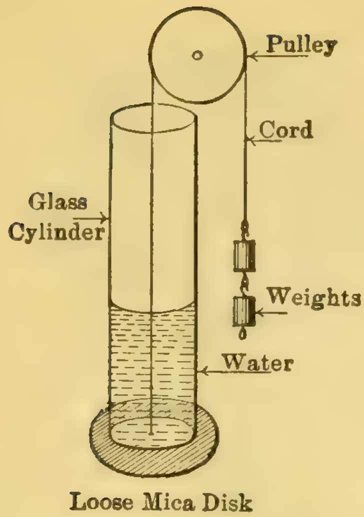


FIGURE 43.—The greater the depth of water, the more weights must be added to hold a disk against the bottom.

In both cases the weight of each water layer is added to the weight of all the layers below, so that in the pipe we have many layers resting on a small area, while in the pan few layers are spread over many square inches. It is easily seen that there is a greater weight of water pushing down on a square inch of surface on the bottom of the pipe than on a corresponding area of the shallow pan. We see, therefore, *that the gravity pressure of a liquid upon a surface is directly proportional to the height of the liquid* pressing upon that surface. We see illustrations of this fact in the greater pressure at basement

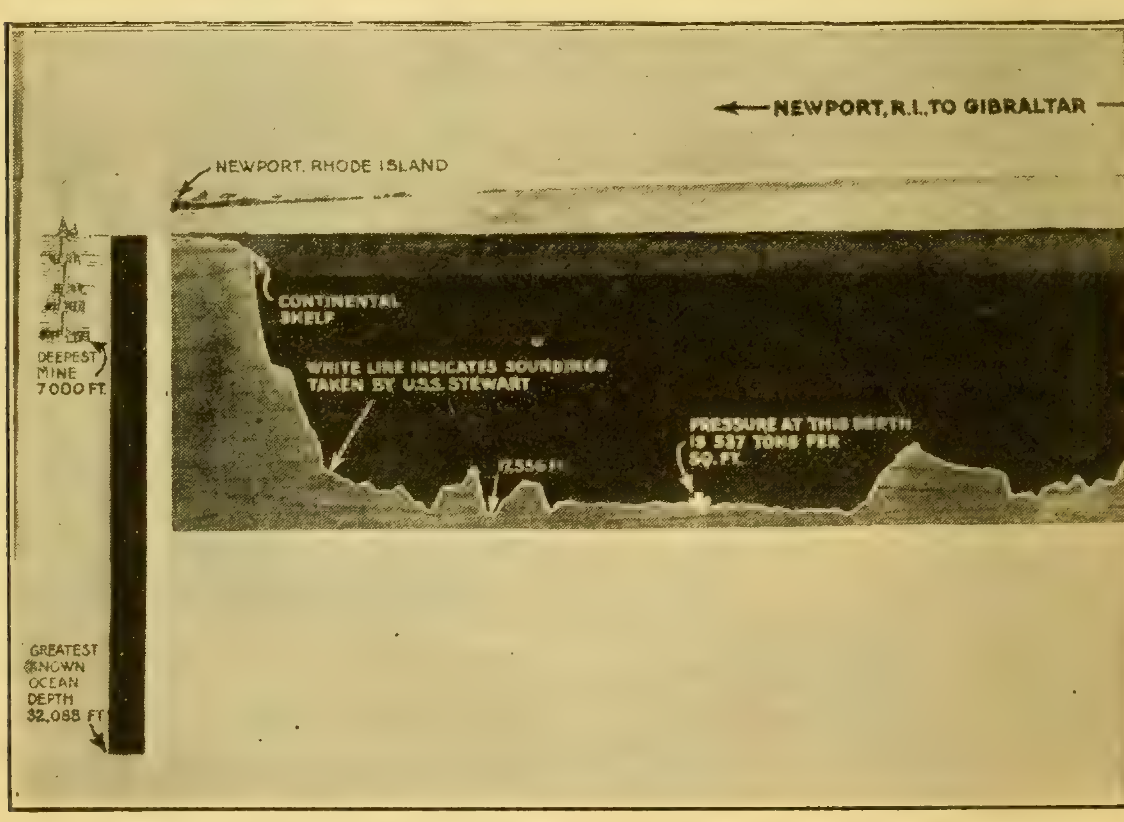


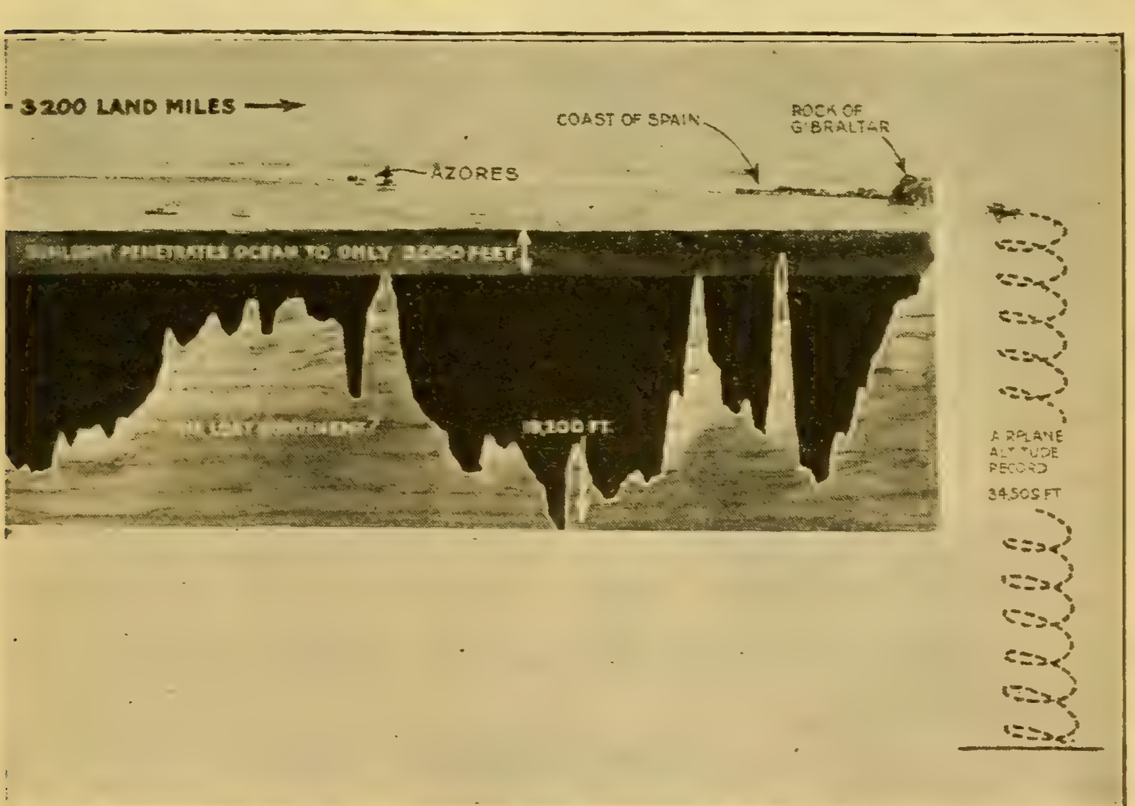
FIGURE 44.—
From this section of the Atlantic Ocean the tremendous

faucets than at those on upper floors, and in the great pressures that must be borne by deep-sea divers (Figure 45).

If mercury, instead of water, is used in the pipe mentioned above, there would be a much greater pressure, since mercury is over 13 times as dense as water. Each square inch of bottom area would have to support over 13 times as much weight. So we see that the *gravity pressure of a liquid is directly proportional to the density of the liquid.*

The two factors that determine gravity pressure, then, are the *height* of the liquid *above* the surface pressed upon, and the *density* of the liquid.

34. Total Gravity Force. — The total pressure or total liquid force on the bottom of the pipe or pan is as many



Courtesy Popular Science Monthly.

OCEAN DEPTHS.

pressure in the deep part of the sea may be realized.

times as great as the pressure per square inch, as there are square inches in the bottom. The total force on a horizontal

Courtesy Popular Science Monthly.

FIGURE 45. — DEEP-SEA DIVING SUIT.

Even with this heavy steel armor, a diver can work only at the comparatively shallow depths of the Continental Shelf. (Figure 44.)

submerged surface is equal to the product of the depth of the liquid times the density of the liquid times the area of the given surface. If, for example, it is desired to find the total liquid force on an area of 10 ft^2 submerged horizontally 25 feet below the surface of water in a lake, we find the product of:

$$\text{height} \times \text{density} \times \text{area} = \text{total force.}$$

$$25\,ft \times 62.5\,lbs/ft^3 \times 10\,ft^2 = 15{,}625\text{ lbs,}$$

which is the total force exerted by the liquid against the submerged surface.

The relation just stated may be expressed by a simple formula. Let *h* represent the perpendicular height of the liquid above the surface pressed upon; let *d* represent the density of the liquid; and *a* the area of the submerged surface. Then the total liquid force *F*, against the submerged surface is,

$$\mathbf{F = hda.}$$

It follows from the above that neither the depth of the liquid beneath the surface pressed upon, nor any horizontal dimension of the liquid affects the pressure. The pressure of the atmosphere cannot be determined in this way because the density of the air is not uniform.

35. Sidewise and Upward Pressures. — The pressure of liquids against vertical surfaces is frequently seen. The very fact that we store or carry water in tanks or pails is evidence that the water is pushing out sidewise against the walls of the tank or pail. If the water had no sidewise

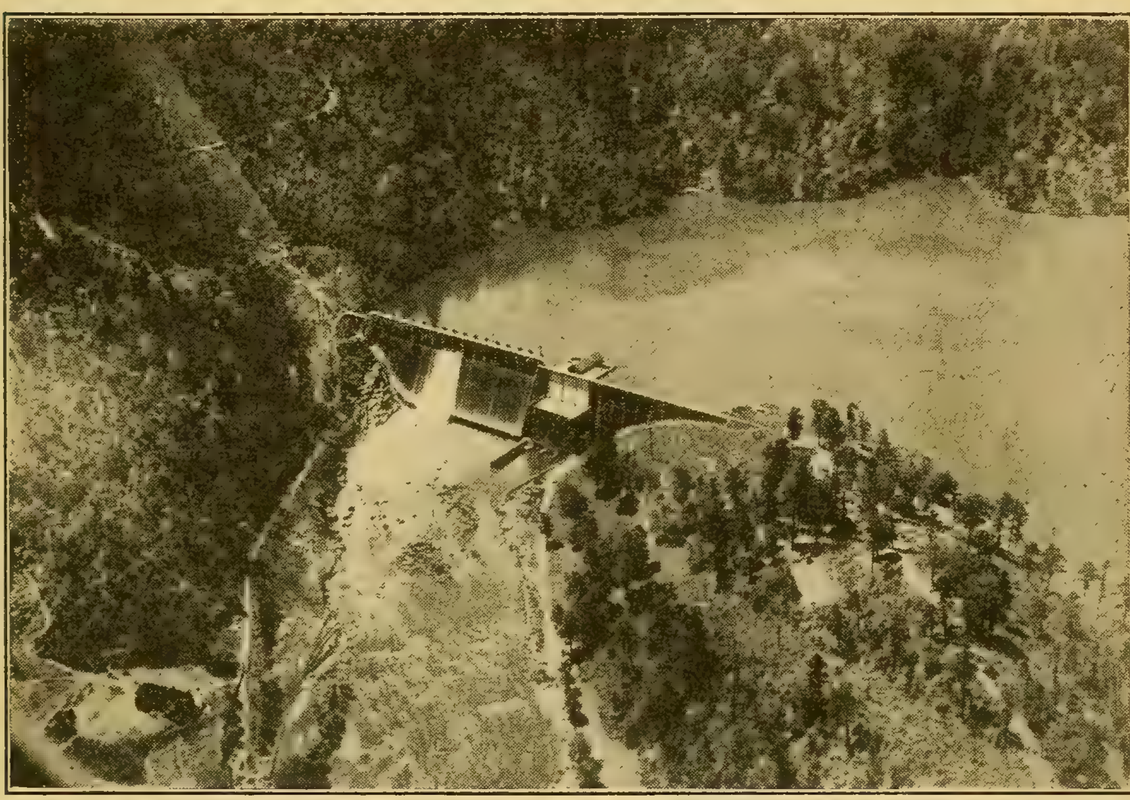


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FIGURE 46. — THE MATHIS DAM IN GEORGIA.

The dam is much thicker at the bottom because of the increase of pressure with depth. The size of the lake does not affect the pressure.

pressure, it could be carried or stored on flat surfaces without the necessity for side walls. If a hole is made through the side of a water tank near the bottom, the water spurts out horizontally with considerable force. Dams of great thickness (Figure 46) are required to hold in check the horizontal pressure against them. Wooden tanks are bound with iron hoops to withstand the pressure on their vertical surfaces.

The reason for horizontal pressure lies in the fact that the molecules of a liquid are freely moving. They may be compared to shot or marbles in a pail. The bottom layer of shot is forced apart by the pressure of the layer just above. This pressure pushes them sidewise against the wall of the pail, as well as downward against the bottom of it. But the second layer presses on the first not only because of its own weight, but also because of the weight of all the layers above it. So the sidewise push against the wall results from the weight of all the water (or shot) above the area whose pressure is being considered. Since this pressure is transmitted in all directions equally, it depends only upon the density of the liquid and the perpendicular distance between the unit area pressed upon and the free upper surface of the liquid. In this respect it is precisely similar to the downward pressure on a horizontal surface.

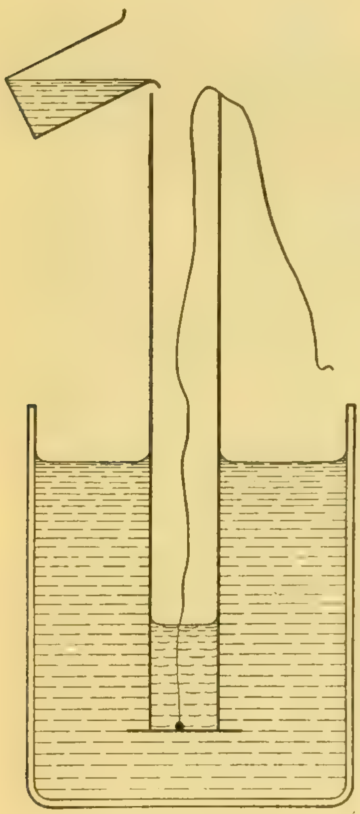


FIGURE 47.

The total force on a side wall of a reservoir of liquid is the sum of all the pressures on all the unit areas of the wall. The upper parts will have less pressure per square inch and the lower parts more pressure, because of the difference in the height of the liquid above them. *The total force on the wall will be the product of the area and the average pressure;* that is, the pressure at the middle point of the wall. On a dam, whose length is 400 ft and against which the water presses to a height of 30 ft, the total force would be computed thus:

Average pressure against the dam in lbs/ft^2 =

average depth × density of water:

$$15 \text{ ft} \times 62.5 \text{ lbs/ft}^3 = 937.5 \text{ lbs/ft}^2.$$

Average pressure × area = total liquid force.

$$937.5 \text{ lbs/ft}^2 \times 12{,}000 \text{ ft}^2 = 11{,}250{,}000 \text{ lbs},$$

total liquid force against the dam.

The upward pressure of liquid is illustrated by the rise of water in the pipes of a house, by the spurting of water up through a leak in the bottom of a boat, and by the floating (§ 47) of all light objects. Since the same factors determine this pressure, it follows that the upward pressure at a given depth equals the downward pressure at that depth. This equality of pressures can be shown as follows:

EXPERIMENT 14. — Fasten a cord with sealing wax to the center of a mica disk large enough to cover the bottom of a glass cylinder. Pass the cord up through the cylinder and, holding the disk against the cylinder, press that end of the cylinder down into a jar of water. Upward pressure of the water will now support the disk. Then pour water into the cylinder (Figure 47), and it will be found that when the water in the cylinder is just at the level of the water outside, the disk will fall of its own weight. This shows that at the depth of the disk, or at any depth, the downward pressure of the water in the cylinder is equaled by an upward pressure of the water outside.

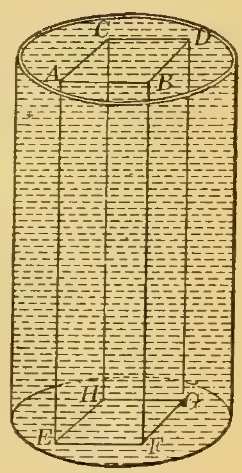


FIGURE 48. — The liquid column *EADG* has the height *EA*.

A single statement may be made concerning the amount of pressure on *any* submerged surface no matter in what position the surface may lie: *the total gravity force on any submerged surface is the weight of a column of liquid whose area is the area of the submerged surface, and whose height is the depth of the center of the submerged surface below the upper surface of the liquid* (Figure 48).

36. Pressure Independent of Shape of Vessel. — If a cubic foot of water is poured into a tank with sides sloping outward and with a small horizontal bottom (Figure 49), it follows that the total liquid pressure on the bottom will be much less than 62.5 lbs, for it will be only the weight of the column of water directly above the bottom. The rest of the weight will be supported by the flaring sides.

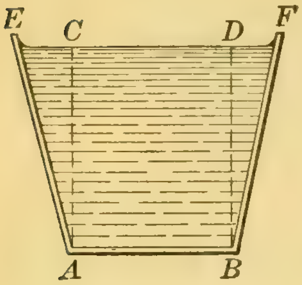


FIGURE 49.—Only the column *ABCD* exerts pressure on the bottom.

This may be illustrated by a set of vessels called Pascal's vases (Figure 50). The bottom of each of these has the same area. Each vase may be mounted in turn over a rubber disk, against the bottom of which is a pivoted pointer. The other end of the pointer moves over a scale. When water is poured in one of the vases, mounted as indicated, the pressure of the water depresses the rubber diaphragm and causes the pointer to move. If water is poured into each in turn to

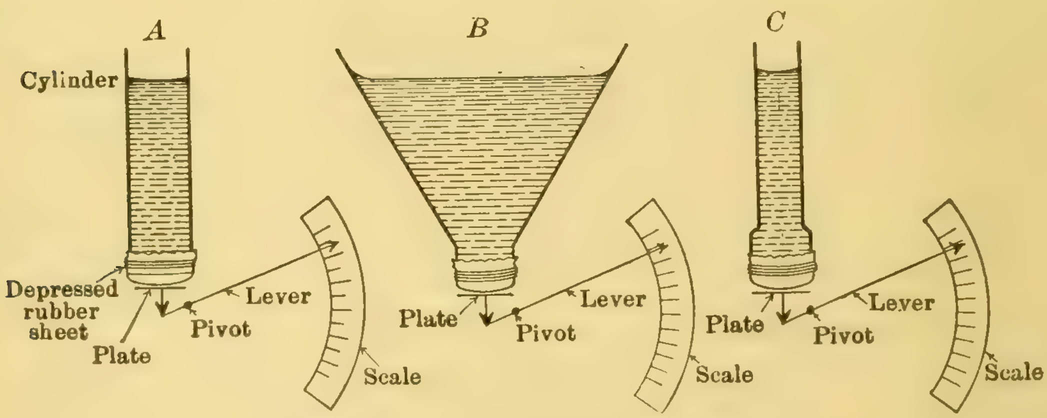


FIGURE 50. — PASCAL'S VASES.

The same force on the bottom is shown by the arrows, although the weights of water in *A*, *B*, and *C* differ greatly.

the same height, the pointer always rises to the same point, showing that the same total pressure is exerted on the bottom in each case. *The pressure* on the bottom of any vessel,

then, *does not depend upon the shape of the vessel, nor the weight of water in it.* The fact that different weights of water may exert the same pressures upon the bottom of different vessels is sometimes called the "hydrostatic paradox."

37. Liquid Surfaces. — The surface of water in a pail or in an undisturbed pond appears flat or horizontal. If a pail of water is dipped out of a pond, the pressure is diminished at that point. The higher pressures of the water around cause the water particles to sink until the pressures are again equal. This can only occur when the surface is level. When we look over a large body of water like the ocean, or along a straight canal, either measurement or observation shows that the surface follows the curvature of the earth. In any body of still water, every point in the surface is equidistant from the earth's center. Therefore water surfaces are really curved whether the eye can perceive the curvature or not.

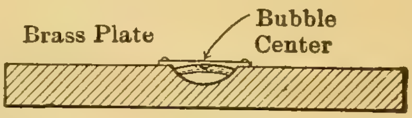


FIGURE 51. — A LEVEL.

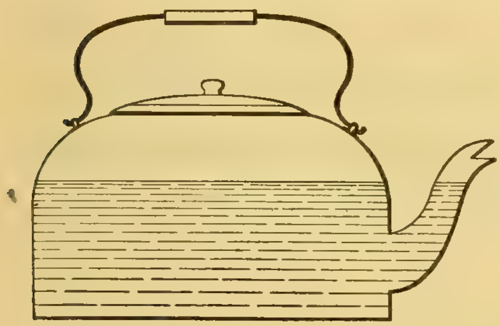


FIGURE 52. — WATER SEEKS ITS LEVEL.

A carpenter's level is a slightly convex tube nearly filled with liquid but containing an air bubble (Figure 51). The bubble is always at the highest point of the tube. When the bubble is at the middle point of the tube, the two ends of the level must be equally elevated and the surface on which the level rests must be horizontal.

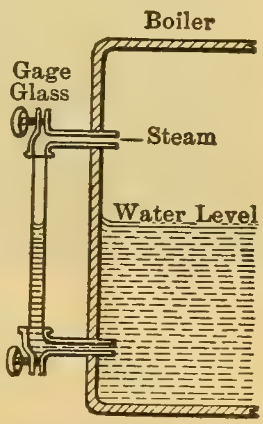


FIGURE 53. — WATER GAGE.

38. Level in Communicating Vessels. — The level of a liquid in tubes or vessels that

are connected to each other will be the same in each, because the depth and hence the pressure at the lowest point

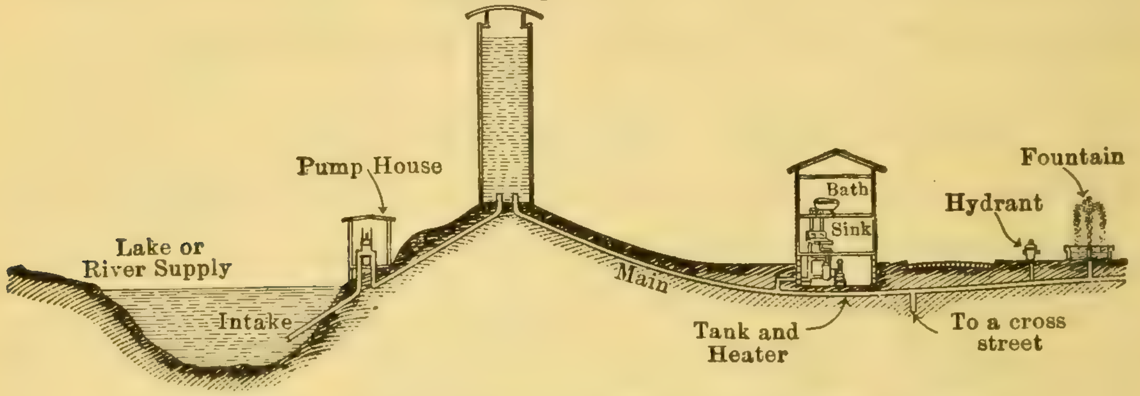


FIGURE 54. — WATER SUPPLY SYSTEM WITH STAND-PIPE.

in the connecting tube is the same in both directions. The level of water in a tea-kettle is no different from that in the spout (Figure 52). Use is made of this in a gage-glass on boilers, where a small vertical glass tube, communicating with the boiler above and below the water level, indicates the height of the water inside (Figure 53.)

FIGURE 55. — This stand pipe gives pressure for a small town.

Cities which are fortunate enough to be able to store water in reservoirs located in near-by hills, may distribute this water by gravity pressure directly. It will rise in pipes as high as the level of the reservoir. Due to resistances of the pipe and of the air, the water will not rise so high if directed upward from a fire-hose nozzle. Cities in flat countries obtain a gravity pressure by pumping the water into tall cylindrical tanks, called *stand-pipes*, usually placed on the highest

land in or near the city (Figure 54). It is interesting to note that the diameter of the stand-pipe is of no importance in causing the pressure necessary to distribute the water (Figure 55). Large diameters are necessary only to prevent a rapid lowering of the water in the stand-pipe when it is being used faster than it is pumped in.

SUMMARY

Pressure of a liquid with a free upper surface is due to the weight of the liquid. When the sides of the vessel are vertical, the pressure of the liquid against the bottom is the weight of the liquid.

Pressure should be expressed in units of force per unit of area, as 60 pounds per square inch.

The gravity pressure of a liquid depends upon two factors — vertical height of the liquid above the surface and the density of the liquid.

The total gravity force is found by multiplying the pressure per unit area by the number of units of area. This is expressed by an equation; $F=hda$. F is the total force required, h the vertical height of the liquid above the surface, d the density of the liquid, and a the area pressed upon. **Whether the area is horizontal or not,** the depth to the center of the area should be taken.

Pressure is independent of the shape of the containing vessel.

Water is commonly distributed in cities by gravity pressure. This may be directly from reservoirs in higher land, or from stand-pipes into which the water has been pumped.

Liquid levels in communicating vessels are always the same.

EXERCISES

1. Why do liquids exert pressure? In what directions is this pressure exerted?

2. What expressions are correct to use in stating pressures?

3. What factors determine the amount of liquid pressure on a unit surface?

4. To what is the downward pressure in a vessel with vertical sides equal?

5. A sink 60 cm $\times$ 40 cm is filled to a depth of 24 cm with water. Find the pressure on the bottom. Find the total force on the bottom.

6. From the dimensions given in the previous problem, determine the total force against one side and against one end.

7. Water in a reservoir stands 115 ft above the outlet of a hydrant. Find the pressure per in^2, and the total force against the hydrant cap, whose area is 4 in^2.

8. A pressure of 80 lbs per in^2 at street level is desired for an hydraulic elevator in an office building. How high must the water in the storage tank stand above the street?

9. What will be the total force against the elevator plunger (Question 8) the area of which is 75 in^2, when the end against which the water presses is (*a*) 26 ft below street level; (*b*) 84 ft above street level?

10. A pail is made with flaring sides. Its height is 12 in, its bottom area is 50 in^2, its top area is 113 in^2, and when filled it holds 39 lbs of water. Find the total force of the water against the bottom.

11. If the pail in the above problem had been made with the large end down, what would be the total force on the bottom when filled?

12. Water fills a tank 10 ft long, 5 ft wide, and 6 ft deep. Find the total force (*a*) on the bottom, (*b*) on one side, (*c*) on one end.

13. A swimming pool has a sloping bottom 75 ft long by 30 ft wide. The water is 8 ft deep at one end and 4 ft deep at the other. Find the total force on the bottom; on the 8 $\times$ 30 end: on the 4 $\times$ 30 end.

14. Gasoline, whose density is 0.7 that of water, fills a tank $6 \times 4 \times 4$ ft deep. Find the total force on the bottom, the side, and the end.

15. Calculate the pressure at the bottom of a column of mercury $2\frac{1}{2}$ ft high and 1 in^2 in cross section. Mercury has a density 13.6 times that of water.

16. Find the total liquid force acting against a dam 400 ft long and against which the water stands to a height of 32 ft.

17. Is it possible for a liquid to exert less pressure on the bottom of a vessel than the liquid weighs? Explain. Can it exert a pressure greater than its weight? Explain.

18. If a slanting pipe and a vertical pipe are connected at the bottom and filled with water, how will the level of the water in the two pipes compare? How will the pressure at the bottom of the pipes compare?

19. Explain how gravity pressure is used to distribute water in the city supply systems.

20. In what kind of locality would you expect to find a stand-pipe in use in connection with a water supply system? What purpose is served by the stand-pipe?

21. (*a*) How is the pressure within the system affected by the diameter of the stand-pipe? (*b*) How is the pressure affected by the height of water in the pipe?

22. In view of your answer to (*a*) in the previous question, why should any system need a stand-pipe of considerable diameter?

23. Why is the lower portion of a stand-pipe made of stronger plates than the upper portion?

24. The basement floor of a building is 92 ft below the level of the water in a stand-pipe. Calculate the pressure per in^2 at the basement of the building and at each of the three floors above, if the floors are 11.5 ft apart.

25. It is a common saying that it is easier to swim in deep water than in water 4 or 5 ft deep. Express your opinion as to the effect of the depth of the water *beneath* the swimmer on the water pressure against the swimmer.

26. Deep-water fish are kept in specially fitted pressure tanks in an aquarium. Why is this necessary?

27. What is the pressure per in^2 at the opening of a caisson 69 ft below water level? How is water prevented from entering this opening?

28. Is there a limit beyond which submarines may not safely submerge? Why is this true? At what depth is a pressure of 45 lbs/in^2 encountered?

CHAPTER IV

TRANSMISSION OF FLUID PRESSURE AND PASCAL'S LAW

39. Nature of Fluid Pressure. — Fluid pressure consists of the push of the molecules of a fluid against each other

Courtesy Kennedy Valve Mfg. Co.

FIGURE 56. — In this test of the Boston Fire Department the great pressure of the water throws the streams to a great height.

and against the walls surrounding the fluid. A fluid presses at right angles against the walls surrounding it. This

is seen when a flat hose becomes rounded from the pressure exerted in all directions on its inner wall by the water rushing into it.

40. Transmission of Pressure. — The pressure of a liquid may be due to (1) gravity pressure arising from its weight (§ 31) and (2) pressure applied to the liquid from without. We are to consider here how the pressure of an inclosed liquid is affected by applying an outside force to the liquid.

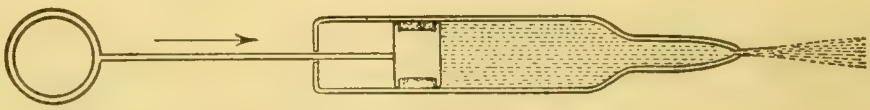


FIGURE 57. — The water transmits the pressure of the piston.

EXPERIMENT 15. — Push the handle of a glass squirt gun (Figure 57) filled with water. The water spurts out of the nozzle with considerable force. The pressure exerted by the piston is carried through all the water in the barrel even to that issuing from the nozzle.

Although the pump in the water works station may be several miles from a faucet, the pressure of the pump piston is transmitted by the water in the pipe to the water just back of the faucet and causes this water to rush out when the faucet is opened. Further, a pressure gage (§ 32) at the pump and one at the *closed* faucet will show the same number of pounds pressure per square inch ; that is, the pressure has been transmitted unchanged.

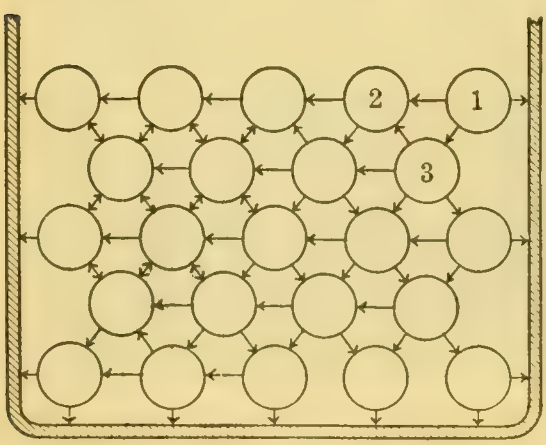


FIGURE 58. — Pressure applied to molecule 1 is transmitted to molecules 2 and 3, and from them to the other molecules, as indicated by the arrows.

The molecules of a liquid are very free to move, and great pressures produce only a very slight compression in a

liquid. We can picture the molecules that actually touch the piston as pressing on their neighbors, just as if they were steel balls instead of molecules of water (Figure 58). This pressure is handed on from molecule to molecule, so that the pressure on one layer of molecules spreads throughout the entire body of the inclosed liquid. The molecules touching the walls inclosing the liquid exert their pressure against these walls. Hence the walls are subject to the same pressure as that applied to the piston. That is, if the piston is 1 cm^2 in area, the force transmitted to 1 cm^2 (pressure per cm^2) of any part of the liquid, or of the walls, will be the same as that exerted by the piston. If the piston is 1 in^2, the pressure per in^2 will be the same throughout.

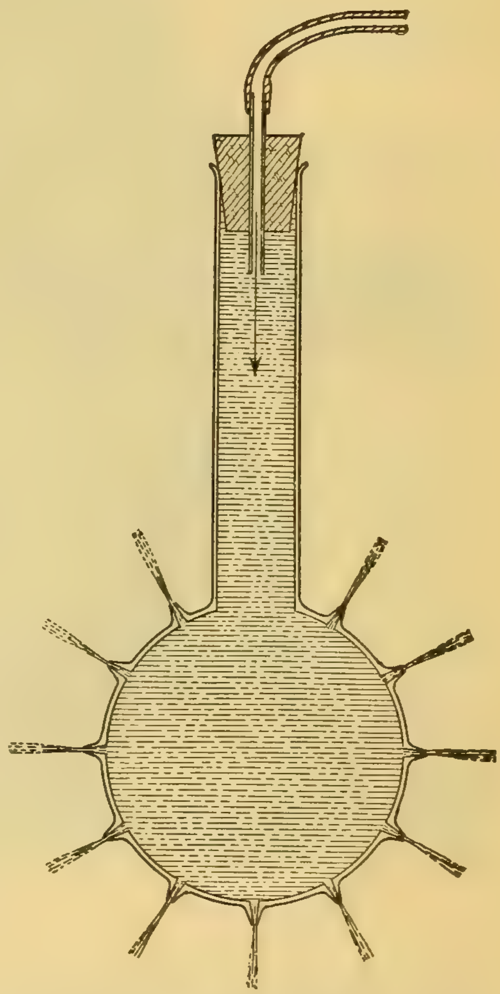


FIGURE 59. — The length of the jets shows equal pressure.

41. Pascal's Law. — The principle of the transmission of pressure was first stated by the French scientist, Pascal, in 1653, and is commonly known as Pascal's Law. It applies to all fluids, that is, to gases as well as liquids, provided they are completely inclosed and are at rest. Pascal's Law states: *Pressure applied from without to an inclosed fluid is transmitted equally in all directions without loss, and acts with equal force on equal surfaces.*

Pascal's Law is illustrated by attaching to a faucet a glass

bulb that has several openings or nozzles (Figure 59). When the faucet is opened, water spurts with equal force out of all the nozzles. Although it might be expected that water would press with the greatest force out of the lower nozzle, pressure gage readings show that this is not the case. The pressure at the faucet is transmitted equally and in all directions throughout the glass globe.

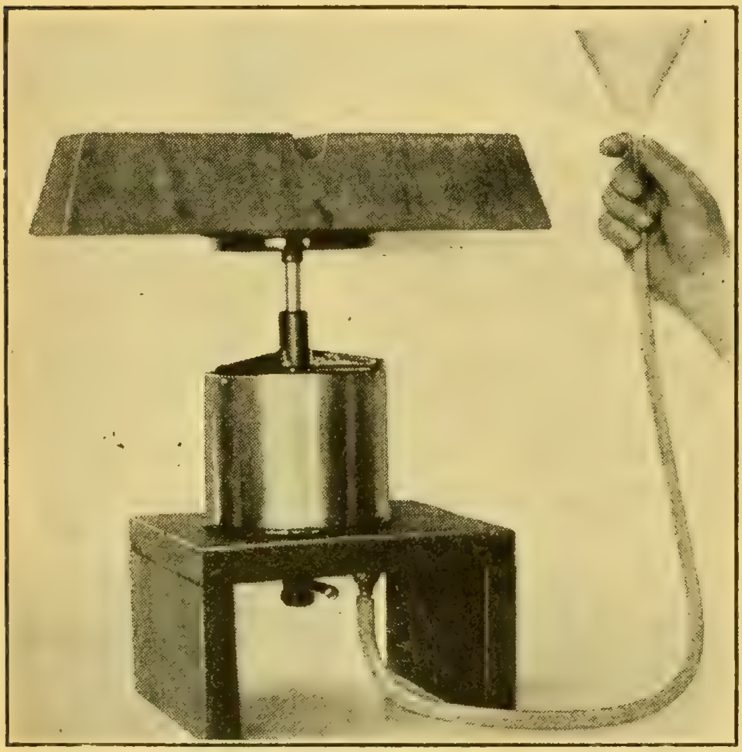


FIGURE 60. — WEIGHT LIFTER.

Another application of Pascal's Law is shown in the following experiment.

EXPERIMENT 16. — The apparatus (Figure 60) consists of a cylinder containing a tightly fitting piston. Into the bottom of this cylinder leads a tube of small diameter connected with a vertical rubber tube and funnel. Pour some water into the rubber tube. *What happens?* Allow more water to enter and place a weight on top of the piston. Keep increasing the weight on the top as long as the water pressure can lift the total weight. *How does the weight lifted compare with the weight of the water in the narrow vertical tube? How does this experiment illustrate Pascal's principle?*

The weight lifter used in the last experiment can be made with a top large enough for a man to stand upon. The pressure through a small water pipe will be enough to lift a man. Pascal burst a strong cask by means of the pressure of water in a vertical pipe that fitted tightly into the top of the cask (Figure 61). Closely allied to the weight lifter is another de-

Blaise Pascal (1623–1662) was an exceedingly versatile French philosopher, mathematician, and scientist. Passing over his remarkable work in mathematics, we find his influence on physics represented by his experiments showing the change of air pressure with altitude; his experiments in the statics and dynamics of liquids; and his statement of the well-known law of the transmission of pressure by fluids (Pascal's Law).

vice known as the *hydrostatic press,* which is the most useful application of Pascal's Law.

42. The Hydrostatic Press. — This is a machine capable of exerting enormous force, invented in 1796 to take advantage of the principle of transmission of fluid pressure. It is often spoken of as the *hydraulic press.*

The diagram in Figure 62 shows a large piston, *P*, and a small one, *p*,

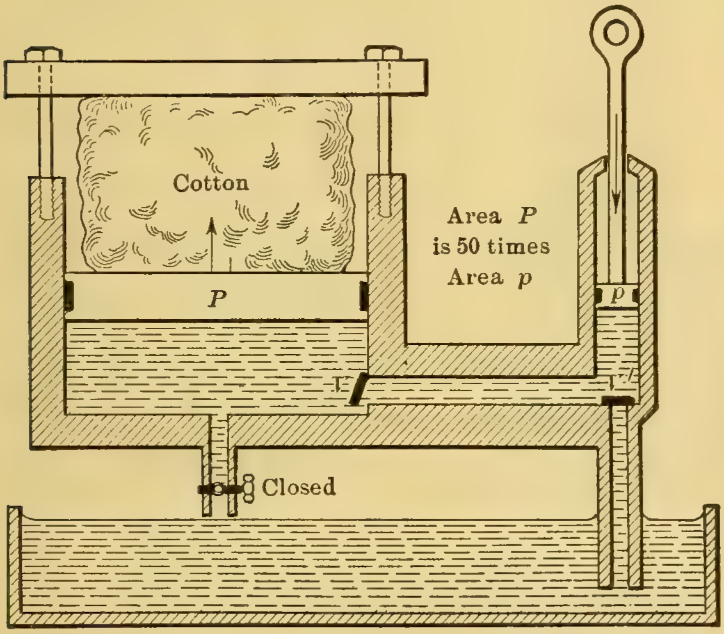


FIGURE 62. — DIAGRAM OF A HYDROSTATIC PRESS.

each fitted water tight into a cylinder. The space between the two cylinders is filled with water. If the pistons were of the same size, any force applied to the one would be transmitted unchanged to the other. The second piston would be pushed up by the liquid with the same force with which the first piston pushed down on the liquid. But if, as shown, the large piston has 50 times the area of the small piston, a

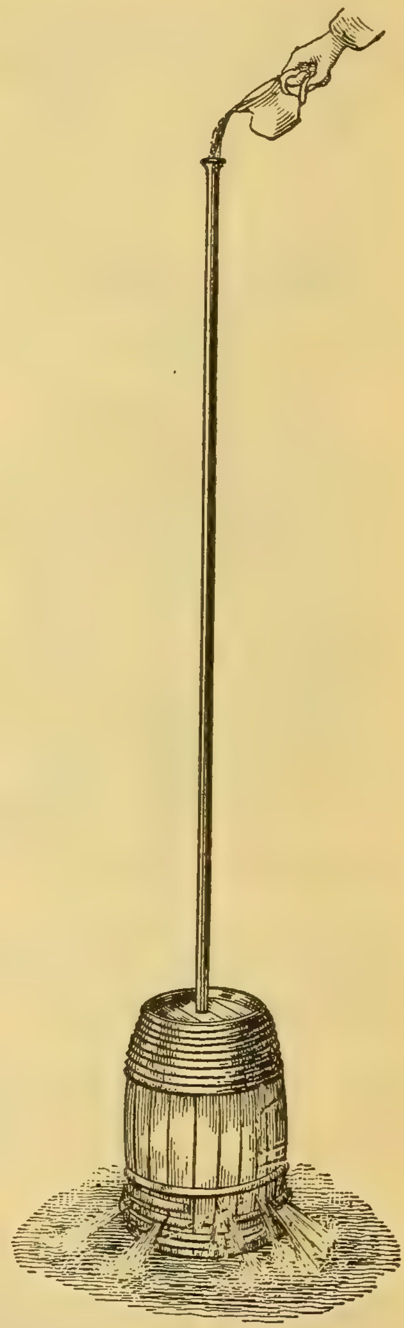


FIGURE 61. — The pressure of the water in the pipe is breaking the cask.

10-pound force applied to the small piston will exert a force of 50 × 10 lbs = 500 lbs on the large piston, since the surface of the large piston has 50 portions, each the size of the small piston. The *pressure* is the same throughout the press, but the total force against the large piston is 50 times as great as that against the small piston, because its area is 50 times that of the small piston.

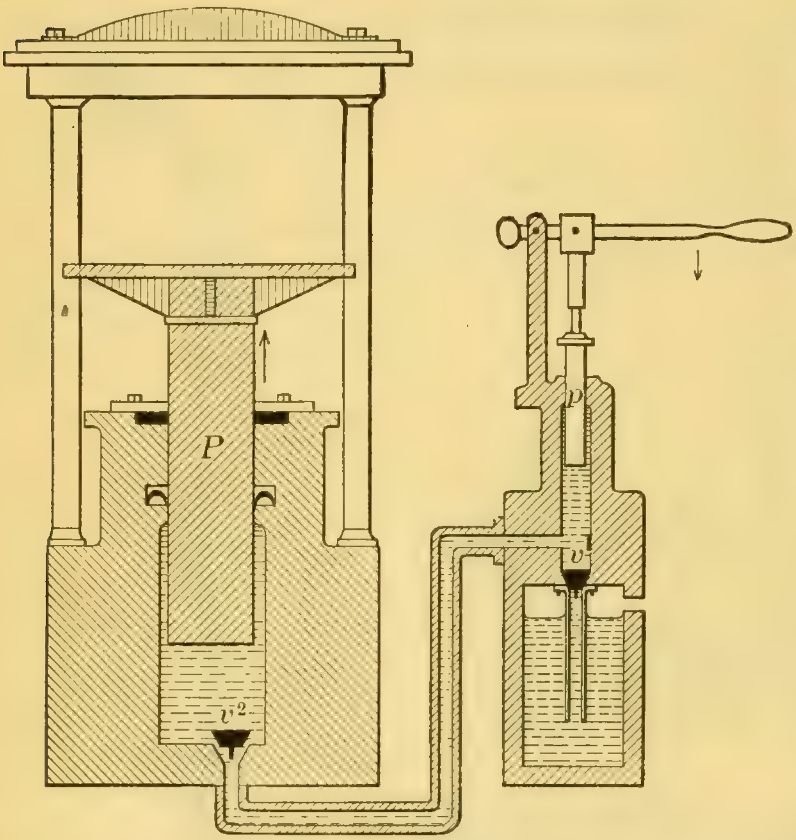


FIGURE 63. — SECTION OF A COMMERCIAL PRESS.

Note the thickness of the walls and the shaped packing, which prevents the water from leaking around the large piston.

Representing the forces by f for the small piston and F for the large piston, the areas by a and A, respectively, and the diameters by d and D, the following relation may be stated for the hydraulic press:

$$\frac{f}{F} = \frac{a}{A} = \frac{d^2}{D^2}$$

In general, the force exerted by the large piston of a hydraulic press is as many times as great as that exerted on the small piston, as the area of the larger piston is times as great as the area of the small piston. That is: *The forces are directly proportional to the piston areas.*

The great gain in force obtained by the hydraulic press is not secured without a corresponding loss in another way. In pushing the small piston down, only a little water is moved into the large cylinder. This water, spread over the large piston, raises it only a little. A small piston, that can develop 50 times its own force on a larger piston, has to move through 50 times as great a distance as that through which the larger piston is moved. This means practically that the small piston has to move many feet in order to move the large piston a fraction of a foot. We are willing, however, to exert our effort through this much greater distance in order to gain a much greater force.

During the operation of the press, the check valve, v^2, prevents the liquid in the large cylinder from flowing back during the upstroke of the small piston. The valve, v, permits the entrance of more liquid to the small cylinder during the upstroke, and prevents the liquid already present from flowing back into the reservoir on the downstroke (§ 72).

PROBLEMS

1. The piston areas of a hydraulic press are respectively 4 in² and 40 in². The small piston exerts a force of 30 lbs. What is the total force on the large piston?

Answer. Since the area of the large piston is 10 times that of the small, 10 times as great a force will be exerted upon it, that is, 10×30 lbs or 300 lbs.

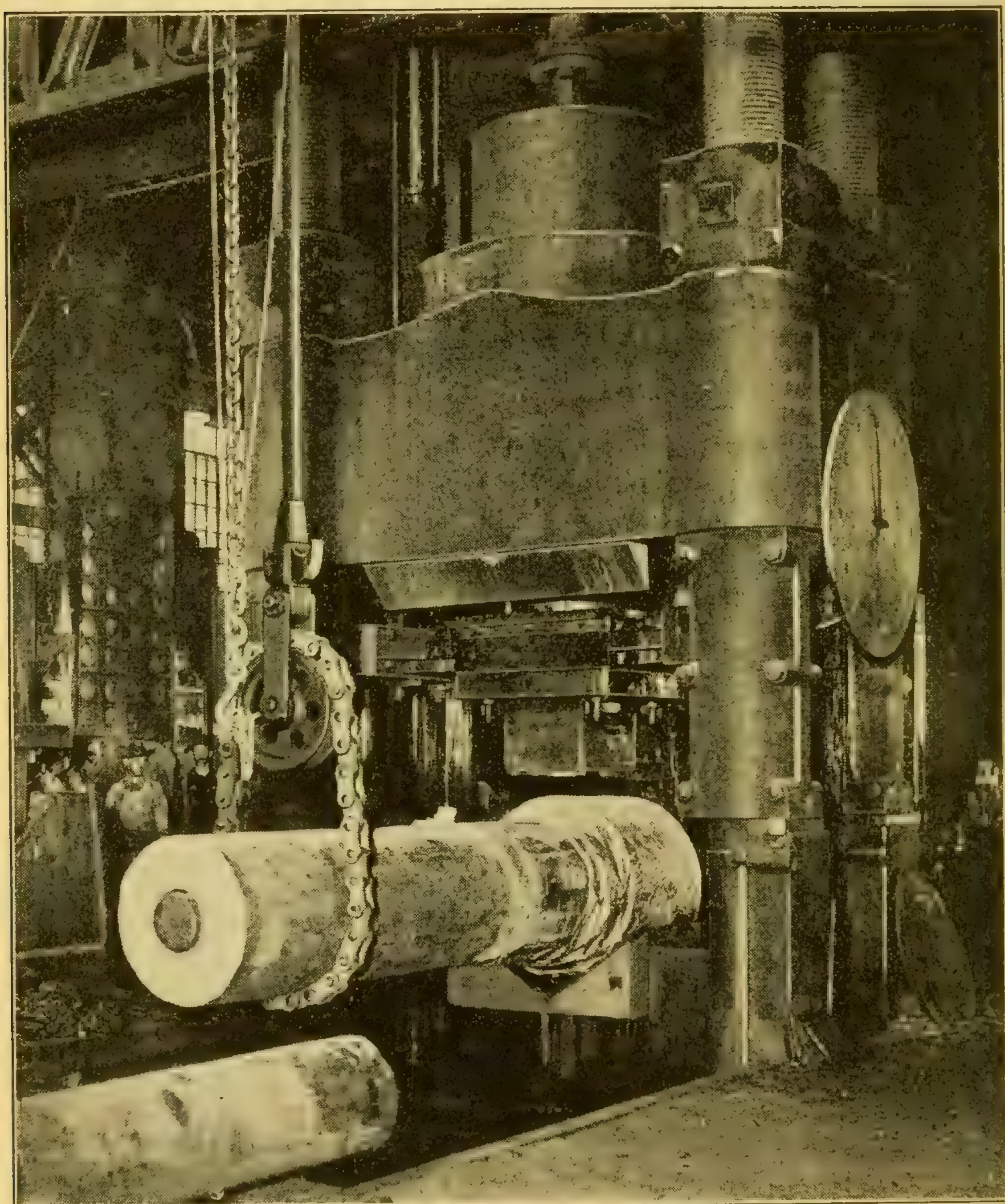
2. The two pistons in a hydraulic press are respectively 1 inch and 5 inches in diameter. What force can be applied by the large piston, if the small piston exerts a force of 20 lbs per in²?

$d = 1$, $D = 5$, $f = 20$, and F is to be found. Substituting in

$$\frac{f}{F} = \frac{d^2}{D^2}: \quad \frac{20}{F} = \frac{1}{25}.$$

Solving: $F = 500$ lbs, *Answer.*

3. The two pistons in a hydraulic press have a diameter ratio of 1 : 30. What is (*a*) their area ratio; (*b*) the ratio of the pressure against each; (*c*) the ratio of the forces against each; and (*d*) the ratio of the distances moved by each?



Courtesy Popular Science Monthly.

FIGURE 64. — HYDRAULIC PRESS FORGING A CANNON.

The small cylinder or pump that furnishes the pressure is some distance away. The top of the press is adjusted to the proper working distance by means of the large screws shown at the corners. The dial on the side indicates the pressure being applied.

4. The larger piston of a hydraulic press has a compressing force of 288,000 lbs and pistons that are respectively 3 inches and 36 inches in diameter. What force is applied by the small piston?

5. The diameters of the pistons of a cotton press are 2 inches and 30 inches respectively. What resistance can be overcome by a force of 800 lbs on the small piston?

6. A hydraulic press has pistons respectively 1 inch and 20 inches in diameter, and 45 lbs force is exerted by the small piston. What is the force on the large piston? How far will the large piston be moved while the small piston is making 80 ten-inch strokes?

43. Uses of the Hydraulic Press. — In commercial presses, oil or alcohol is frequently substituted for water. Such presses are used for baling cotton, riveting and forging steel (Figure 64), forcing lead through a die to form lead pipe, lifting heavy weights, and for all other purposes for which great pressure is desired. Among the most familiar applications are dentists' and barbers' chairs, and hydraulic elevators.

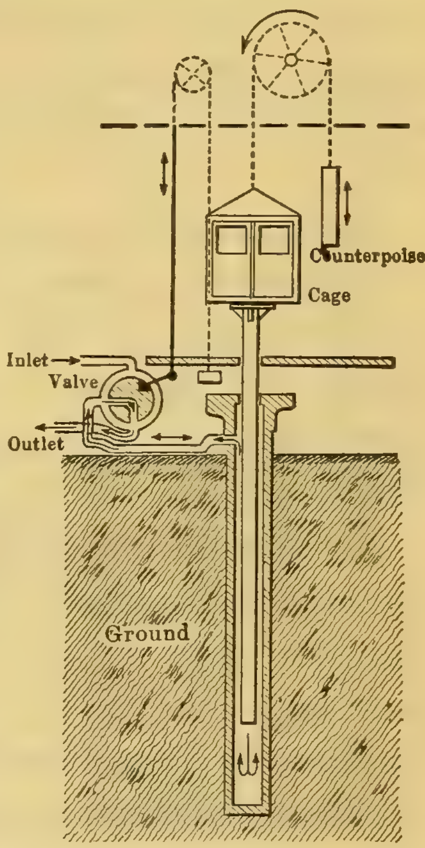


FIGURE 65. — HYDRAULIC ELEVATOR.

The rope at the left operates the valve, shown turned so the elevator can descend.

For elevators, the water is pumped into closed tanks partly filled with air; the air is compressed and exerts its pressure upon the water. This high-pressure water is admitted under the piston of the elevator and causes it to rise (Figure 65). To permit the car to descend, a valve is opened by the operator, thus allowing the water to run out of the cylinder into open tanks that furnish the supply for the pumps that feed the pressure tank.

SUMMARY

Fluid pressure consists in the push of the molecules of a fluid against each other and perpendicularly against the walls surrounding the fluid.

The pressure of a liquid may be due to (1) gravity pressure caused by its weight and (2) pressure applied to the liquid from without.

Pascal's Law states: Pressure applied from without to an inclosed fluid is transmitted equally in all directions without loss, and acts with equal force on equal surfaces. Fluids transmit pressure without loss because they consist of freely moving molecules.

The **hydrostatic press** (hydraulic press) is a machine that takes advantage of the operation of Pascal's principle. The press consists of a large cylinder and a small cylinder each containing a tightly fitting piston. A liquid between the cylinders transmits to the large piston the pressure exerted on the smaller piston, so that the larger piston may exert an enormous force.

The general law of the hydraulic press: The force exerted by the large piston of a hydraulic press is as many times as great as that exerted on the small piston, as the area of the larger piston is times as great as the area of the smaller piston. **The forces are directly proportional to the piston areas.**

Using small letters for the force, area, and diameter of the small piston and capitals for the large piston, the general law of the press is represented by:

$$\frac{f}{F} = \frac{a}{A} = \frac{d^2}{D^2}$$

The great gain in force obtained by means of the hydraulic press is secured by making the small piston move through a much greater distance than that through which the large piston moves.

Hydraulic presses are used for bailing cotton, for pressing out vegetable oils and juices, for forging steel, in dentists' and barbers' chairs, in the operation of elevators, and as hydraulic jacks.

EXERCISES

1. What is meant by fluid pressure?

2. To what two things may the pressure of a liquid be due?

3. Why is it possible for a fluid to transmit pressure in all directions, while a solid can transmit pressure in one direction only?

4. State Pascal's Law and illustrate its application by a diagram.

5. Explain the weight lifter (Figure 66). Compare the *pressure* exerted at the mouth with that against the piston. Compare the *total force* on the air in the tube with that at the piston.

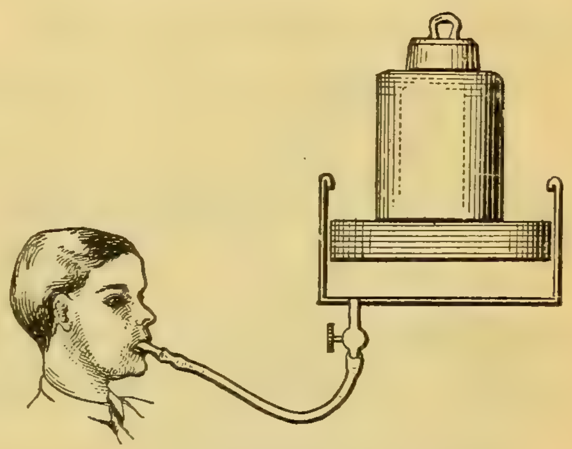


FIGURE 66.

6. Make a diagram of a hydraulic press with reservoir and return pipes. On the drawing indicate areas, pressures, and total forces.

7. A hydraulic press has pistons whose areas are in the ratio of 1 to 900. When a force of 40 pounds is exerted against the smaller, what force will be exerted against the larger? If the smaller piston is moved through 45 ten-inch strokes, how far will the larger piston move?

8. The two pistons in a hydraulic press have a *diameter* ratio of 1: 25. What is (*a*) their area ratio; (*b*) the ratio of the pressures against each; (*c*) the ratio of the forces against each; (*d*) the ratio of the distances moved by each?

9. A pressure of 500 lbs/in^2 is exerted on the small piston of a press. What total force will be exerted against the larger piston, which is 20 inches in diameter? What is the ratio of gain in force by using this press? (Small piston area = 1 in^2.)

10. Explain the operation of the hydraulic elevator. How does Pascal's Law apply to it?

11. Give three industrial uses for which large hydraulic presses are employed. Give three uses for which small presses would be sufficient.

12. Why does a hydraulic elevator usually run slowly? Why is it a safe type of elevator?

13. The pistons of a hydraulic press are respectively 1 and 16 inches in diameter. What force applied to the small piston will enable the large one to exert a compressing force of 50 tons?

14. In Figure 66, the area of the piston is 30 in^2. The boy exerts a pressure of 12 oz/in^2. How heavy a weight is lifted?

15. Explain the use of the long pipe in Figure 61.

16. Why is it necessary to take such care in packing the pistons of the hydraulic press?

17. Airplanes are launched from battleships by the small piston of an *inverted* hydraulic press. Compare the speed of the plane with that of the large piston.

18. Some brakes are operated by hydraulic pressure. Does this method permit of equal application to the different brakes; of easy regulation of the amount of pressure; of easy change of direction of the pressure?

CHAPTER V

FLOATING AND SUBMERGED BODIES

44. Buoyancy and Flotation. — The effect of fluids in floating some bodies and apparently lessening the weight of others is one of the most widely observed natural phenomena. While bathing, the arms seem to be lifted by some hidden force. A stone or anchor suddenly grows heavier as it is lifted out of the water (Figure 67), if one is to judge by the effort required to lift it. This buoyant effect of the water can be explained by one or two simple principles.

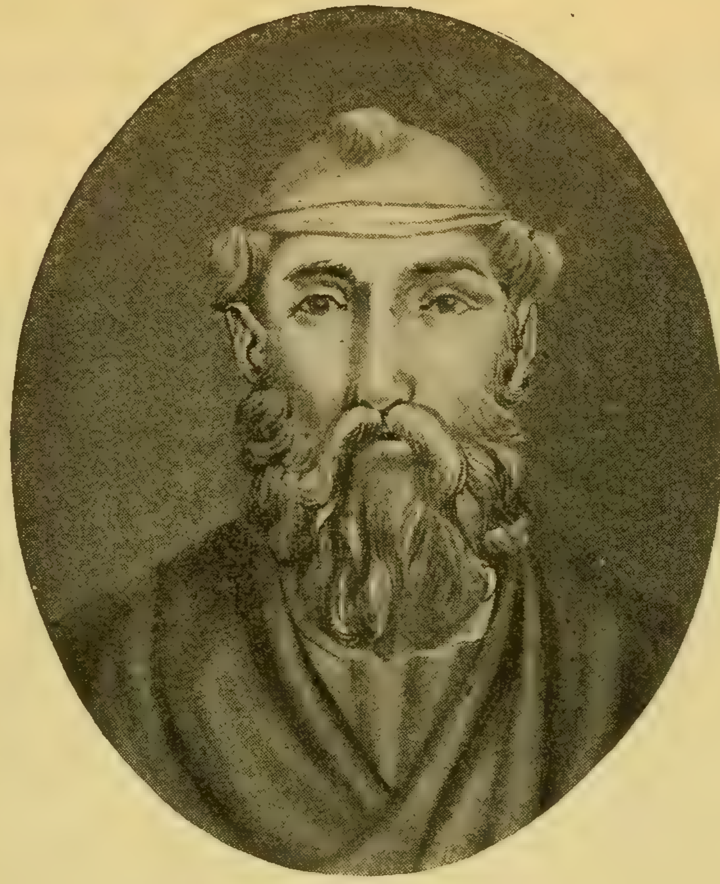
FIGURE 67. — LIFTING THE ANCHOR.

45. Archimedes' Principle. — Like many other important physical principles, it remained for a master mind to discover the relations which are involved in the buoyancy of fluids. Archimedes was probably not the first man to observe in his bath the buoyancy of the water upon his body, nor the first to notice the rise of the water in the tub as his body was immersed in it. But he is credited with being the first to deduce and state the relation between these two phenomena.

Tradition relates that Archimedes was asked by Hiero, the ruler of Syracuse, to ascertain whether a certain crown was composed of pure gold or alloyed with silver. Archimedes, pondering this question in his bath, noted the decrease in his weight while in the water and the simultaneous rise of the water in the tub. He noted also that as more of his body was immersed the higher the water rose and the lighter his body appeared. In this, then, was the solution of his question, for he concluded at once that the apparent loss in the weight of his body and the weight of the water displaced by it must be equal.

Experimental proof of this conclusion was simple. Then, he reasoned, since gold is a denser metal than silver, a crown of a certain weight of gold would be smaller than one of the same weight of silver. It would displace less water, when immersed, and lose less weight than an alloyed crown of the same weight. If the equal weights of gold and alloy were in cubical form, the difference in size would be readily noticed. The irregularities in the shape of the crown made the direct method of comparison impossible. Upon immersion, the crown was found to be lighter than a gold crown should be, and was accordingly judged to be an alloy.

Stated simply, Archimedes' conclusion may be given thus: *An immersed body is buoyed up by a force equal to the weight of the fluid which it displaces.* The word *fluid* here used indicates that the law holds good for gases as well as liquids. The buoyant force of air is less noticeable on account of the small weights of air which common articles displace. But when the articles are large and light, such as balloons and dirigibles, this buoyancy serves to lift them (Figure 68). It is interesting to note that in very accurate weighing, the air displacement of the weights and the article being weighed



Archimedes (287–212, B.C.) was primarily a mathematician but he was the inventor of many practical machines and appliances. In physical science he is best known for his discovery of the relationship between the buoyancy and the displacement of fluids, and for the principle of machines. It is said that in demonstrating the effectiveness of small forces applied to suitable machines, he arranged apparatus whereby Hiero, the ruler of Syracuse, was able to move a loaded ship. Archimedes was so little impressed by the value of his practical inventions that he left no account of them. It is only from tradition that we learn of most of his scientific work. His ability as a reasoner is shown by the deduction of the principle which bears his name (§ 45).

must be calculated and a proper allowance made for the loss resulting from such displacement.

46. Experimental Proof of Archimedes' Principle. — The buoyant force of the water on an anchor is acting in a direction opposite to the weight of the anchor. To verify

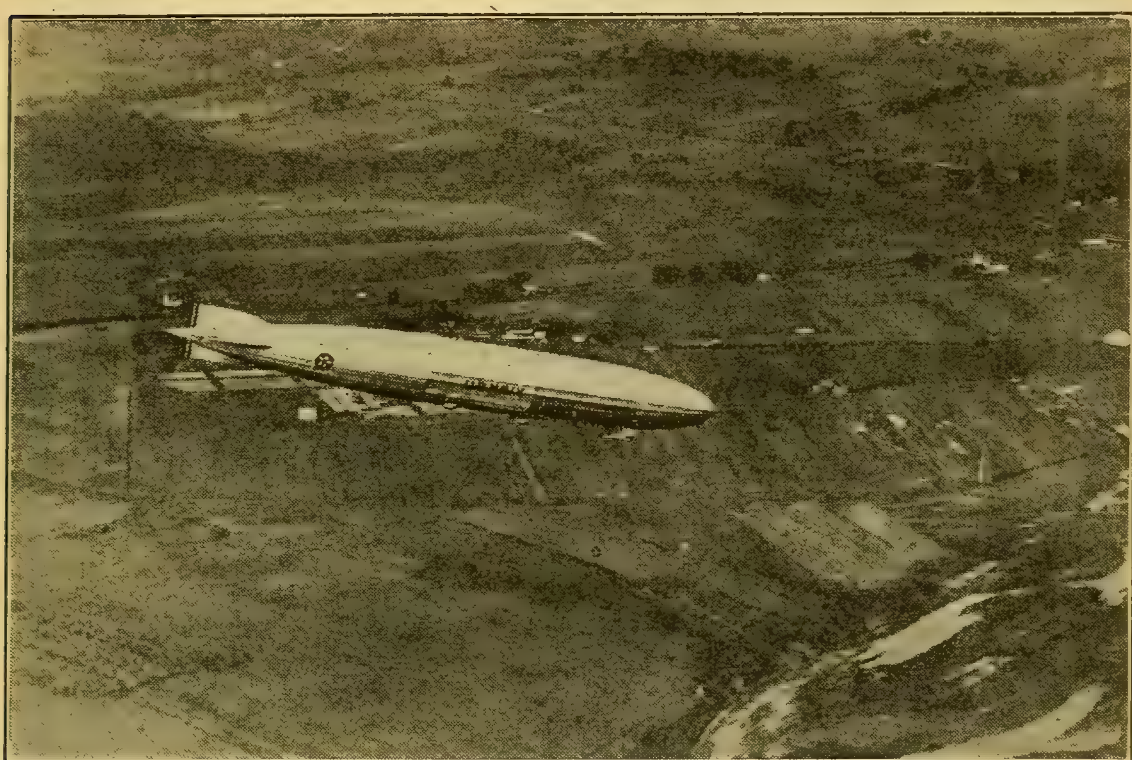


FIGURE 68. — A DIRIGIBLE IN FLIGHT.

The difference between the weight of the helium in the dirigible and the same volume of air gives buoyancy enough to support the airship.

the principle of Archimedes, we must show that the apparent loss of weight of an immersed body is equal to the weight of the liquid it displaces.

EXPERIMENT 17. — A brass cylinder is made so as to fit exactly into a bucket. Hang the bucket and cylinder on a hook beneath the left-hand pan of the balance (Figure 69). Counterpoise the bucket and cylinder by putting weights into the other pan. Immerse the cylinder in water. *Which side is now lighter? Why?* Pour water into the bucket until the balance is restored, and note that the bucket is now just full.

Since the cylinder just fits the bucket, the volume of water poured into the bucket equals that of the water displaced by the cylinder. *What did you see that showed that the weight of the water poured into the bucket equals the weight of the water displaced by the cylinder? Has this experiment verified Archimedes' Law? How?*

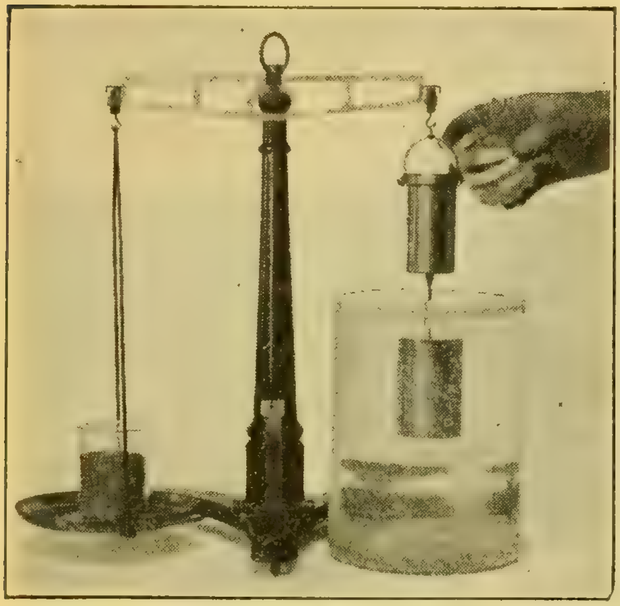


FIGURE 69. — CYLINDER AND BUCKET. The cylinder looks larger than it is because it is magnified by the water.

QUESTIONS

1. What common phenomena illustrate the buoyancy of liquids on bodies submerged in them?

2. What two observations showed to Archimedes the relation between buoyancy and displacement?

3. State Archimedes' principle. Does this principle apply to gases as well as to liquids?

4. Describe a simple experiment to illustrate Archimedes' principle.

5. A stone weighs 45 lbs in air and displaces 15 lbs of water when immersed. What is the weight of the stone in water? (*Weight in water* means *apparent weight* when submerged.)

6. The weight in air of 10 cm^3 of lead is 113 g. What will be the displacement when immersed in water? What will be the weight in water?

7. What will be the weight in air of 10 cm^3 of iron, if the weight when submerged in water is 66 g?

8. What is the volume in ft^3 of a stone that weighs 506 lbs in air and 381 lbs in water?

9. A boy, who weighs 125 lbs in air, can just float in fresh water when almost entirely submerged. What is his displacement? What is his volume in ft^3?

10. Does the principle of the equality of buoyancy and displacement hold true for bodies partly submerged?

11. A boy displaces about 2 ft^3 of air. This displaced air weighs about 2.5 oz. Do the scales on which the boy weighs himself indicate his actual weight, or more, or less? Explain.

47. Flotation. — A stone sinks in water, because the upward push or buoyancy of the water is less than the gravitational or downward pull on the stone. In other words, the stone goes down because it is heavier than the weight of the water it displaces.

We occasionally see a piece of wood so waterlogged that its weight is nicely adjusted to the weight of an equal volume of

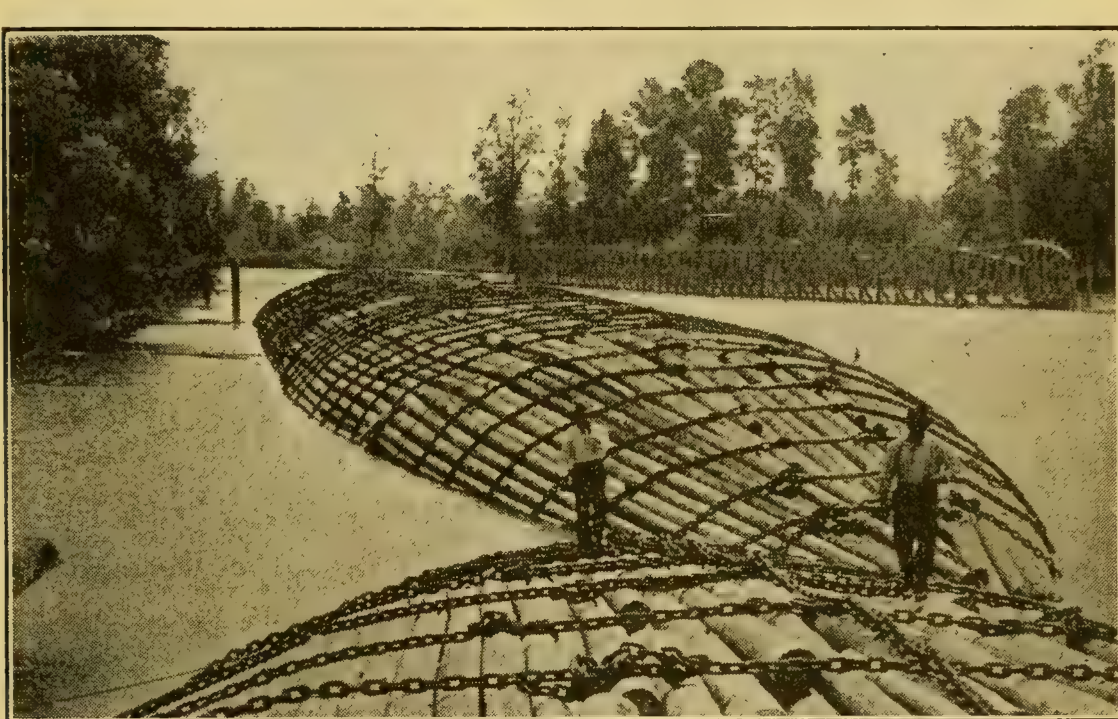


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FIGURE 70. — These giant rafts, constructed on the Columbia River, are floated by sea to San Diego.

water. This body neither sinks to the bottom nor floats with any portion of itself exposed.

Other bodies, such as dry wood or cork, thrown into the water are at once forced back, so that part of their volume is above the surface (Figure 70). This shows that they weigh less than the water that they displaced while momentarily submerged.

Applying Archimedes' principle to floating bodies, we see that: *Any floating body sinks until it has displaced its own*

weight of fluid. This is the *Law of Flotation.* When a body has sunk until equilibrium has been reached, it will be buoyed up by a force equal to its own weight. The upward and downward forces on it are equal, and its position is maintained.

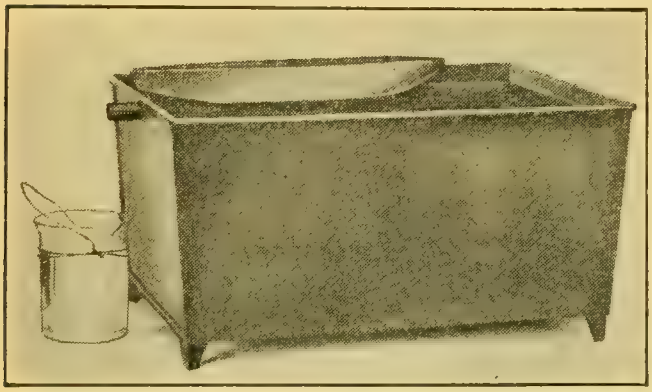


FIGURE 71. — The beaker contains the water displaced by the boat.

EXPERIMENT 18. — Fill the tank (Figure 71) with water so that a little runs out the overflow. Discard this overflow. Place a toy boat in the tank and catch the water which the boat displaces from the tank. Weigh the displaced water. Weigh the boat. Compare its weight with that of the displaced water. *What does this experiment show?*

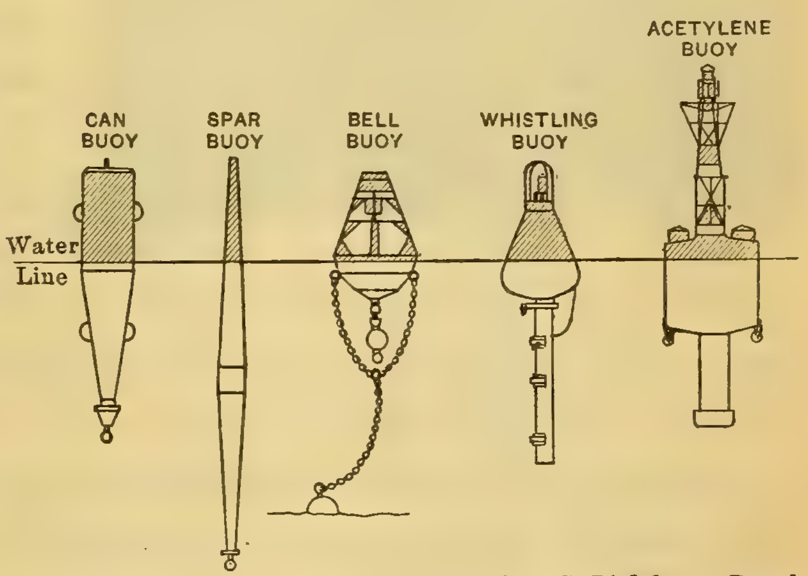
The method of the experiment is not practical for actual vessels of large size. The displacement of a ship, or the number of tons of water displaced by it, can be determined from the weight of the materials of which the ship is built or from the volume of the ship below the water-line (Figure 72).

FIGURE 72. — The light colored part of the hull will be under water when the ship is loaded.

48. Practical Applications of Flotation. — The Law of Flotation applies to many familiar things. The human body weighs slightly less than an equal volume of water. Hence it is possible for a person to float if he submerges enough of his body to displace his own weight of water. When

FIGURE 73. — THE HARBOR AT CATALINA.
Buoyancy supports the boats and buoys.

the head is lifted slightly as in swimming, very little effort properly directed is necessary to keep the body up. A person thrown into the water should come to the surface and float. Unfortunately in some cases the persons struggle so that their lungs admit a little water. This water causes a constriction of the throat and drowning or suffocation may result.



Courtesy of U. S. Lighthouse Board.

FIGURE 74. — TYPICAL BUOYS

A spar-buoy (Figure 74), used to mark the channel for ships, is made of wood with one end weighted to make it stand vertically. It floats partly submerged, the submerged

portion displacing as much weight of water as the whole timber weighs.

The acetylene light buoy (Figure 75) is constructed so as to have an average density less than that of water; this is done by making it hollow. In the same manner, battleships, in spite of heavy armor, machinery, and armament have an average density less than that of water because of the air spaces existing in their compartments. When the ship is torpedoed and water fills the compartments, the average density of the vessel begins to increase. A number of these separate compartments must be filled before the ship becomes so heavy that it can no longer displace its own weight of water. Then it has to sink.

Courtesy of U. S. Lighthouse Board.

FIGURE 75. — AN ACETYLENE LIGHT BUOY.

Voluntary submersion is effected in the submarine (Figure 76) by admitting water into tanks until the boat weighs more than the water it displaces. The submarine reappears at the surface when its weight is lessened by blowing out the water by compressed air.

A drydock (Figure 77) in which ships are repaired, operates in a somewhat similar manner. Water is admitted to

tanks until the dock sinks. When it is deep enough, the ship is brought into the dock, the water is pumped out of the tanks, and its place taken by air. This makes the dock lighter than the water it displaces, so that it rises, lifting the ship with it out of the water.

Wrecked ships are floated by the buoyant force of water applied either directly to them, or indirectly to barges attached to the wreck. In the first case, divers patch the compartments so water can be pumped out of them. Then the weight is less than that of the displaced water and the boat rises. In the other case, the barges are attached to the sunken ship, water is then pumped from the tanks in the barges and they rise on account of the upward pressure of the water on them. As they rise, the ship rises with them.

The buoyancy of a hollow metal ball is made use of in the operation of a float valve

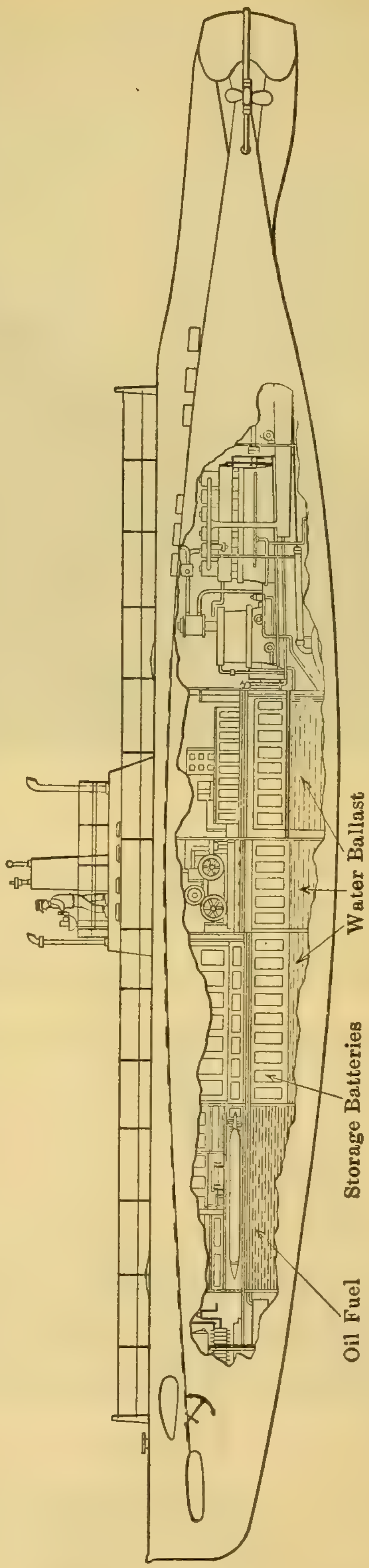
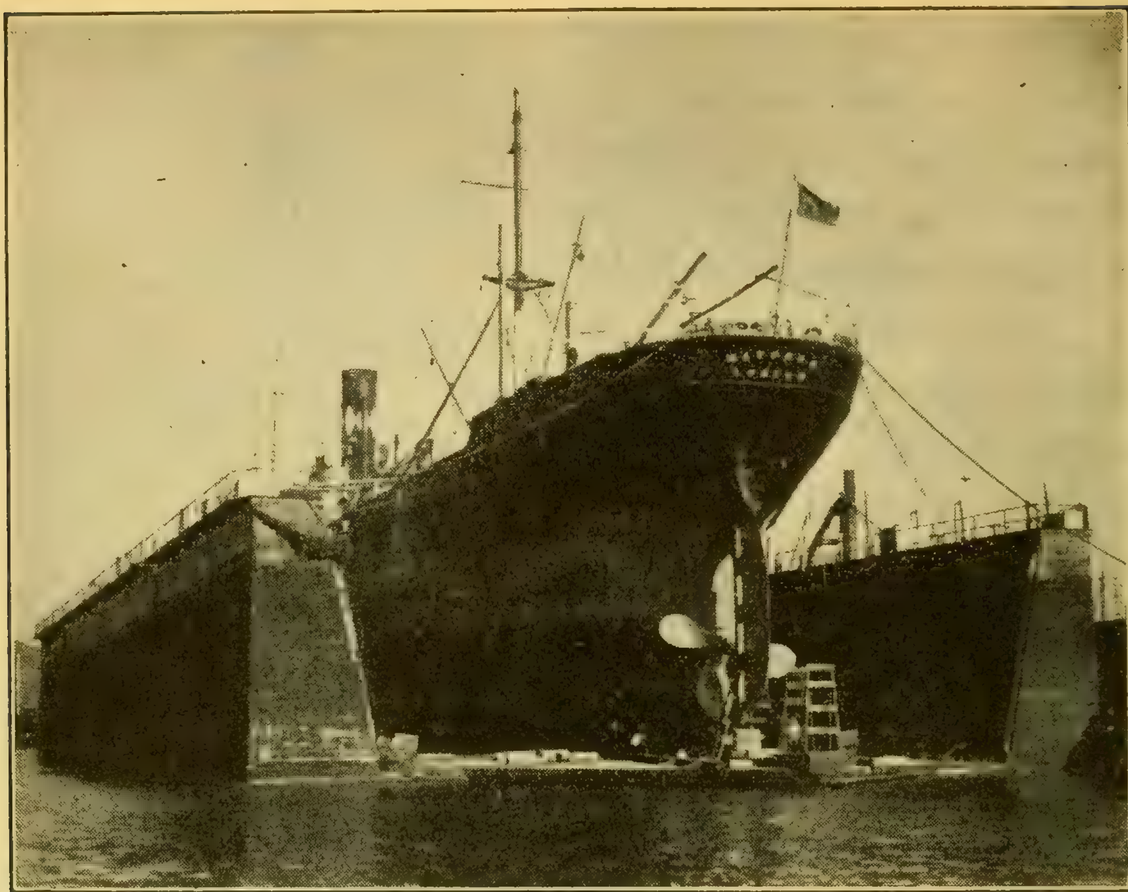


FIGURE 76. — SECTIONAL VIEW OF A SUBMARINE.

The water in the ballast tanks is pumped out when the submarine is brought to the surface. The figure of the man shows the comparative size of the submarine.



Courtesy of the Todd Shipbuilding Corporation.

FIGURE 77. — A LINER IN DRYDOCK.

The water has been pumped out of the dock, its buoyancy has raised the ship above water level, and the hull is now ready to be cleaned and painted.

that maintains a constant water level in a tank (Figure 78). Some mechanical device lifts the plunger, so that water runs out of the discharge pipe. Acting in accordance with the law of flotation, the float drops with the descending water level in the tank. When a certain point is reached in the fall of the ball, the pressure of water in the inlet pipe is able

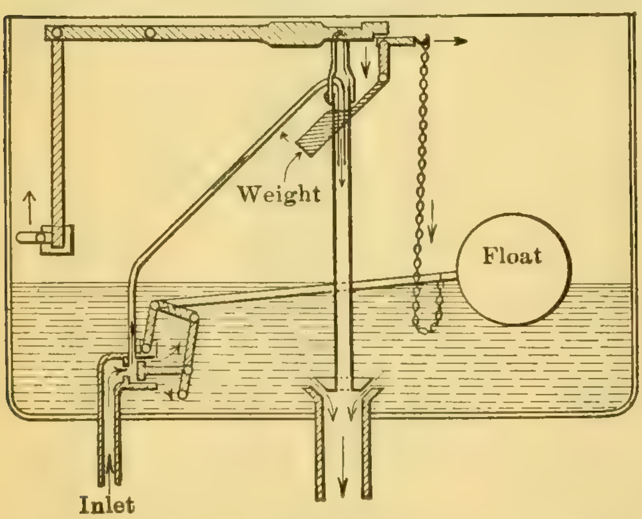


FIGURE 78. — The buoyancy of the float causes it to rise and limits the height to which water will rise in the tank.

to open the inlet valve. When most of the water thus runs out of the tank, the plunger valve closes either by its own weight or by mechanical action, checking the outward flow. Then the rising water in the tank slowly lifts the ball till a point is reached where it closes the inlet valve, by lever action.

FIGURE 79.—IRON ON MERCURY.

The fraction of any floating body that is submerged is equal to the density of the floating body over the density of the fluid. Wood which is $\frac{6}{10}$ times as heavy as water, floats with $\frac{6}{10}$ of its volume submerged when in water, but with $\frac{6}{8}$ of its volume under the surface of oil, which is $\frac{8}{10}$ times as heavy as water.

Iron, which is 7.6 times as heavy as water, floats on mercury, which is 13.6 times as dense as water. A little more than half the iron lies below the surface of the mercury (Figure 79).

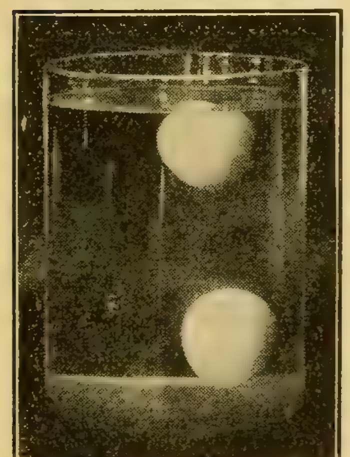


FIGURE 80. — The fresher egg is at the bottom.

The buoyancy of a liquid increases as the density of the liquid increases. A ship passing from salt water into the fresh water of a river sinks deeper because a greater volume of the lighter fresh water must be displaced to equal the weight of the ship. The water is denser where it is saltier, therefore the buoyancy of the ocean water is not the same at all places. The density of the ocean water must be carefully considered in the navigation of submarines.

Eggs may be tested for freshness by putting them in salt solutions of different density. The egg grows lighter but not smaller as it becomes older. A fresh egg sinks in a salt solution that will float a stale egg (Figure

80). A fair estimate of the freshness of the egg may therefore be obtained by knowing the density of a solution in which the egg will just sink.

SUMMARY

A body immersed in any fluid **displaces** a volume of that fluid equal to **its own volume.**

The weight of this displaced fluid equals the buoyant force exerted by the fluid on the body. The body will appear to lose weight by just this amount.

Archimedes' principle states that an immersed body is buoyed up by a force equal to the weight of the displaced fluid. Archimedes' principle is true for gases as well as for liquids.

A floating body displaces a weight of fluid equal to **its own weight.** A ship whose *displacement* is 15,000 tons weighs 15,000 tons.

When a ship or piece of wood has its compartments or pores filled with water it ceases to be a floating body and sinks.

The buoyant force of fluids is made useful in the floating of all ships, in floating balloons, and in some special cases, such as raising wrecks, drydocking ships for repairs, and in toilet tanks.

EXERCISES

1. A block of brass 10 cm $\times$ 4 cm $\times$ 5 cm weighs 1760 g in air. How many grams of water will it displace when immersed? What will it appear to weigh in water?

2. A floating mine weighs 320 lbs. What must its volume be in ft^3 in order to float in sea water which weighs 64 lbs/ft^3?

3. A block of iron 20 cm $\times$ 8 cm $\times$ 5 cm weighs 5200 g in water. What is its displacement? What is its apparent loss of weight when submerged? What will it weigh in air?

4. A stone weighs 81.25 lbs in air, and 50 lbs when immersed in water. What is the displacement of the stone? What is the volume of the stone in ft^3?

5. Explain the buoyancy of cork; of balloons; of steel ships.

6. A timber 16 ft long and 6 in × 6 in square floats with 0.7 of its volume under the surface of water. What does the timber weigh?

7. A square stick of wood is weighted to make it float vertically in water. What fraction of its length will be under water if the stick is 0.6 times as heavy as water? Will a greater or smaller fraction be submerged, if the stick is placed in gasoline?

8. A cube of gold 1 cm on edge weighs 19.3 g; a similar cube of silver weighs 10.5 g; while a similar cube of half silver and half gold weighs 14.9 g. What would each cube weigh while immersed in water? Does each lose the same fraction of its weight? Could a metal be identified by finding the fraction of its weight lost during immersion?

9. An ocean steamer weighs 35,000 tons. What is its displacement in sea water? What is its displacement in fresh water whose weight per cubic foot is about $\frac{1}{40}$ less than that of sea water?

10. Explain why smoke rises on some days while on other days the same kind of smoke settles to the ground.

11. Explain why wood sinks after it becomes waterlogged.

12. Why does a piece of wood float? How deep does it sink? Under what conditions will it sink to the bottom?

13. Why does a stone seem lighter in water than out? What determines the weight it appears to lose when submerged?

14. Why will an iron boat float, while the same amount of iron in a solid mass will sink? Under what conditions will the boat sink?

15. A cubic foot of granite weighs 171.875 lbs. Find (*a*) the weight in air of a block of granite 4 ft × 3 ft × 2 ft, (*b*) the weight of the water it displaces when submerged, (*c*) the weight of the block when submerged.

16. A boat is made of steel which is about 8 times as dense as water. The boat weighs 1500 lbs. Find the number of

ft³ of steel used in making the boat. Find the weight of water it displaces when floating.

17. A cubic foot of sandstone weighs 83.25 lbs when under water. How much will it weigh in air?

18. A rectangular barge whose horizontal dimensions are 60×16 ft sinks 1.5 ft deep in water when unloaded. What does it weigh? When a load of 240,000 lbs is put on the barge, how much deeper will it sink?

19. A piece of wood $1 \text{ ft} \times 1 \text{ ft} \times 10 \text{ ft}$ weighs 325 lbs. What force is required to push it under water?

20. What is the principle of a life preserver? Of separate water-tight compartments in ships?

21. Does a boat entering fresh water from salt water have a higher or a lower water-line? Explain.

22. One cubic foot of aluminum weighs 162.3 lbs. What must be the volume of the smallest block (hollow) into which the 1 cubic foot can be cast and still float? What will be the volume of the inclosed air space?

23. A flatboat 32 ft long by 10 ft wide is used to ferry a 4000-pound automobile across a stream. How many ft³ of water will the automobile cause the boat to displace? How much deeper will the boat sink after being loaded?

24. What is the weight per ft³ of a substance that floats half submerged in water? Will it sink deeper or not so deep in a liquid denser than water? Why?

25. A scow 32 ft long by 12 ft wide, when loaded, sinks 3 ft deep in water. What does it weigh? How much water does it displace? Calculate by the formula $F = hda$ the total force upward against the bottom of the scow.

26. There is a tradition among sailors to the effect that wrecked ships sink to a certain depth and remain there between surface and bottom of the ocean. Give your opinion of this and a reason for it.

CHAPTER VI

SPECIFIC GRAVITY

49. Specific Gravity. — The relative heaviness (or lightness) of substances is of much practical importance. A man can carry a long wooden beam on his shoulder, while he would be unable to stir from the ground an iron bar of the same size. Builders of airplanes and automobiles are constantly searching for relatively light materials that possess great strength. Mercury has to be shipped in small containers, since it is such a heavy liquid. The specific gravity of oils, waxes, and other commercial products is often used as a quick means of identifying them.

The heaviness of a substance is due to the pull of gravity. Since substances, equal in volume, vary in heaviness, the pull of gravity must be stronger on some than on others. As weight is the measure of gravity, the specific gravity of a substance is found by comparing the weight of a certain volume of that substance with the weight of an equal volume of another substance taken as the standard. Water at 4° C is the specific gravity standard for solids and liquids, while air at 0° C and 760 mm pressure is commonly used as a standard for gases.

The specific gravity of a solid or of a liquid is the number of times a certain volume of that substance is as heavy as an equal volume of water.

The specific gravity of 2.6 for aluminum means that any piece of that metal weighs 2.6 times as much as an equal

volume of water. Hence, a cubic centimeter of aluminum weighs 2.6 g, since a cubic centimeter of water at 4° C weighs one gram. A cubic foot of steel, with a specific gravity of 7.7, weighs 7.7×62.5 lbs, the weight of a cubic foot of water. A gallon of kerosene, with a specific gravity of 0.8, is 0.8 as heavy as a gallon of water.

50. Specific Gravity and Archimedes' Principle. — According to Archimedes' principle (§ 45), an immersed body is buoyed up by a force equal to the weight of the liquid which it displaces. This principle gives a convenient means for finding the weight of the "equal volume of water" in determining the specific gravity of irregular pieces of light and heavy solids, provided the solids are insoluble in water. The hydrometer and displacement methods for obtaining the specific gravity of a liquid also make use of Archimedes' principle.

Specific Gravity of Solids

51. Geometrical Solids. — The specific gravity of a regular geometrical solid is readily found by measuring its dimensions and calculating the volume from them. The weight of an equal volume of water is known from the relation that 1 cm^3 of water weighs 1 gram or that 1 ft^3 of water weighs 62.5 lbs. Then the weight of the solid is divided by the weight of the equal volume of water:

$$\textit{Specific gravity} = \frac{\textit{weight of geometrical solid}}{\textit{weight of equal volume of water}}$$

52. Irregular Solids Heavier Than Water. — The volumes of irregular solids are hard to find from measurements of the dimensions. Hence another means is used in finding their specific gravity.

EXPERIMENT 19. — Weigh a lump of coal in air with a spring balance. Then weigh it immersed in water. *What buoyant force is responsible for the apparent loss in weight of the solid? The volume of displaced water is equal to what volume? What is the weight of this equal volume of water? What weight divided by the weight of the equal volume of water will give the specific gravity of the coal? Result?*

The specific gravity of an irregular body heavier than water is found by weighing it first in air and then immersed in water (Figure 81). The apparent loss of weight in water is due to the buoyant force of the water. This force, according to Archimedes' principle, is equal to the weight of the displaced water. The displaced water, however, must have the same volume as the immersed body. Then the apparent loss of weight of the immersed body is equal to the weight of the equal volume of displaced water. Dividing the weight of the body in air by the weight of the equal volume of water gives the specific gravity:

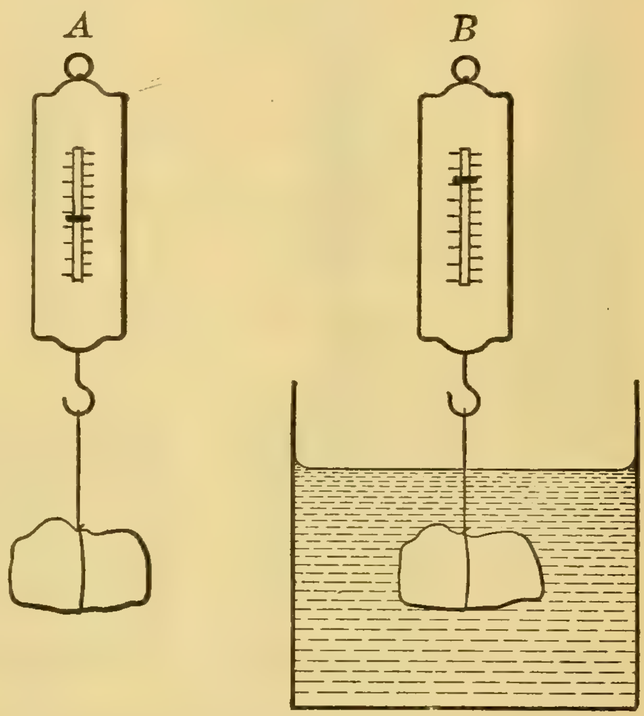


FIGURE 81. — SPECIFIC GRAVITY OF HEAVY SOLID.

A, weighed in air; *B*, weighed in water.

$$\textit{Specific gravity of an irregular body heavier than water} = \frac{\textit{weight of body in air}}{\textit{wt of equal volume of water}}$$

Problem. A lump of coal weighs 152 g in air, and 60 g immersed in water. What is its specific gravity?

152 g − 60 g = 92 g, apparent loss of weight in water
= weight of equal volume of water.

$$\frac{152 \text{ g (weight of coal in air)}}{92 \text{ g (wt of equal volume of water)}} = 1.63, \text{ sp. g.} \quad \textit{Ans.}$$

53. Irregular Body Lighter Than Water. — The sinker method is used for finding the specific gravity of a body that floats in water. The sinker is usually a piece of metal and is heavy enough when attached to the bottom of the body to drag it beneath the surface of the water. These weighings are then made with a spring balance: (1) body in air (Figure 82, *A*); (2) body in air with attached sinker immersed in water (*B*); and (3) body with attached sinker both immersed in water (*C*).

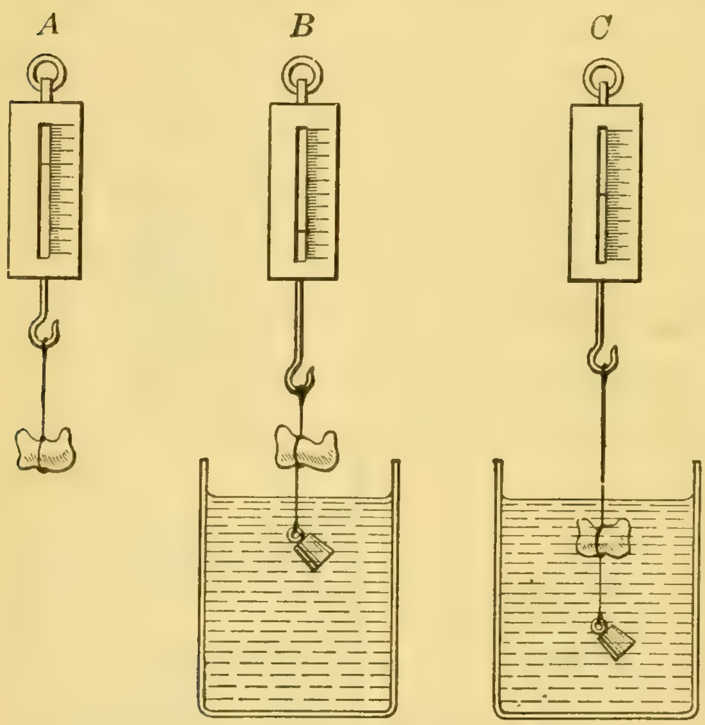


FIGURE 82. — SPECIFIC GRAVITY OF LIGHT SOLID.

Subtracting the third weight from the second gives the buoyant force of the water on the body alone, because the buoyant effect of the water on the sinker is the same in both the second and the third weighings, and so cancels in the subtraction. Dividing the weight in air by the buoyant force found by this subtraction gives the specific gravity, because this buoyant force is the weight of the equal volume of water displaced by the body (Archimedes' principle). The formula, then, for finding the specific gravity of a floating body is:

$$\textit{Specific gravity of an irregular body lighter than water} = \frac{\textit{weight of body in air}}{\textit{wt of an equal volume of water}}$$

54. Geometrical Solid Lighter Than Water. — A simple illustration shows an easy way of finding the specific gravity of a regular geometrical solid that floats in water. A rectangular wooden block will float in water with the larger portion of its volume immersed (Figure 83). The heavier the block, the deeper it will sink. If such a block 5 cm thick is immersed to the depth of 4 cm, a volume of water equal to four-fifths of the volume of the block is displaced. The buoyant force on the block is equal to the weight of this displaced water. Therefore, the weight of a volume of water equal to four-fifths of the volume of the block must be equal to the weight of the whole block. Otherwise this would not float in the way that it did. That is, the immersed portion of the block is four-fifths as heavy as the equal volume of water that it displaces. Its weight is four-fifths that of an equal volume of water, and its specific gravity is 0.8. It will be noted that *the floating block sinks until the fractional part of its volume which is under water is numerically equal to its specific gravity.*

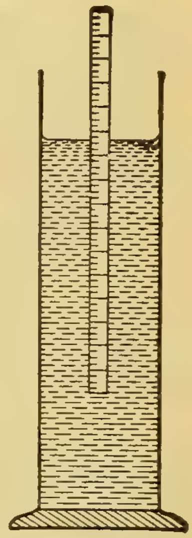


FIGURE 83.

QUESTIONS

1. How does the weight of the fluid displaced by an immersed body compare with the loss of weight of the body when immersed? What principle is involved?

2. What does the loss of weight of a body immersed in water indicate concerning the weight of water of the same volume as the immersed body?

3. Define *specific gravity.*

4. The specific gravity of silver is 10.5. A cubic centimeter of water weighs 1 g. What will be the weight in grams of a silver cube that measures 5 cm on a side?

5. The dimensions of a wooden block are $7.5 \times 7 \times 3.5$ cm, and its weight is 135 g. Find its specific gravity.

6. What is the specific gravity of a glass paper weight that has a volume of 120 cm^3 and weighs 360 g?

7. A cube of glass 4 inches on a side weighs 6 lbs. What is its specific gravity?

8. A lump of granite weighs 30 g in air and 18 g in water. (*a*) What volume of water does the granite displace? (*b*) What is the volume of the granite? (*c*) What is the specific gravity of the granite?

9. A glass bottle weighs 31.2 g in air and 19.2 g in water. How many cm^3 of glass were used in making the bottle?

10. A bar of zinc weighs 71 lbs in air and 61 lbs in water. Find (*a*) its volume; (*b*) its specific gravity.

11. A piece of stone weighs 250 lbs in air and 150 lbs in water. Find the specific gravity of the stone.

12. A cube of iron 10 cm on an edge, weighs 6600 g in water. Find (*a*) its displacement; (*b*) its loss in weight; (*c*) its weight in air; (*d*) its specific gravity.

13. A rectangular block $20 \times 10 \times 5$ cm weighs 4 kg in water. What is its specific gravity?

14. A metal dish used by a chemist weighs 52.5 g in air and 50 g in water. Calculate the specific gravity of the metal. What is the metal? (See table of specific gravities in the Appendix.)

15. A steel rod with a specific gravity of 7.7 weighs 35 g more in air than it does in water. Find (*a*) the weight of the water displaced; (*b*) the volume of the rod; (*c*) the weight of the rod.

16. A piece of stone having a specific gravity of 2.5 weighs 480 g when immersed in water. Find (*a*) its weight in air; (*b*) its volume.

17. A piece of wood alone weighs 8 g in air. With the wood in air and the attached sinker in water, the weight is 22 g. With both the wood and sinker in water the weight is 10 g. (*a*) What is the weight of water displaced by the wood? (*b*) What is the volume of water displaced by the wood? (*c*) What is the volume of the wood? (*d*) What is the specific gravity of the wood?

18. A block weighing 5 lbs in air is tied to a sinker which weighs 20 lbs in water. With both the block and sinker in water, the weight is 16 lbs. Determine the specific gravity of the block.

19. A block of paraffin weighs 50 g in air. With the paraffin and a sinker in water the weight is 264 g. The sinker alone in water weighs 270 g. Find the specific gravity of the paraffin.

20. What is the specific gravity of a piece of wood which sinks until only 0.3 of its volume is above water?

Specific Gravity of Liquids

55. Bottle Method. — The comparison of the weight of a liquid with the weight of an equal volume of water is readily made by the use of a specific gravity bottle, which is a glass-stoppered bottle, accurately constructed so as to contain a definite volume of liquid (Figure 84).

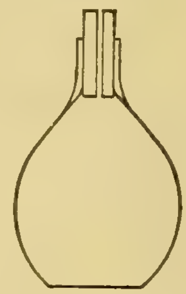


Figure 84. — Excess Liquid Escapes through Hole in Stopper.

Experiment 20. — Weigh a specific gravity bottle empty, and then filled with a solution of copper sulphate. *What weight is found by subtracting the weight of the empty bottle from the weight of the filled bottle?* Weigh the bottle filled with water. *How can you find the weight of the equal volume of water? What is found by dividing the weight of the copper sulphate solution by the weight of an equal volume of water?*

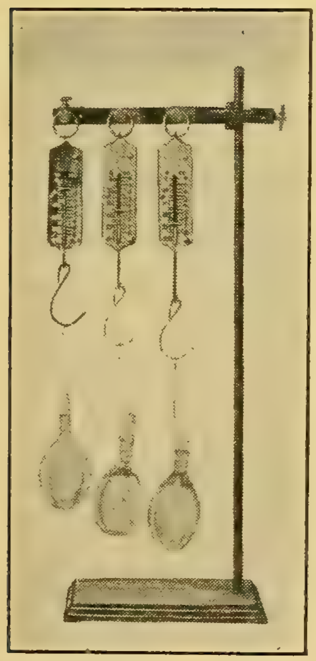


Figure 85. — Left, Empty; Center, Water; Right, Sulphuric Acid.

When the bottle method is used to determine the specific gravity of liquids, the bottle is weighed filled with the liquid whose specific gravity is to be determined (Figure 85). Then it is weighed full of water at the same temperature. The weight of the empty bottle is subtracted from each of the weighings, in order to find the weights of the equal volumes of the two

liquids. Dividing the weight of the given liquid by the weight of the equal volume of water gives the specific gravity of the liquid.

$$\textit{Specific gravity} = \frac{\textit{weight of liquid}}{\textit{weight of equal volume of water}}$$

Specific gravity bottles are marked with the volume in cubic centimeters. Since a cubic centimeter of water weighs a gram, the label gives directly the number of grams of water that it will contain.

Problem. An empty specific gravity bottle weighed 65.3 g. Filled with water, the bottle weighed 115.1 g, and filled with a solution of common salt, the weight was 120.7 g. What was the specific gravity of the salt solution?

120.7 g − 65.3 g = 55.4 g, weight of the salt solution.
115.1 g − 65.3 g = 49.8 g, weight of the equal vol. of water.

$\frac{55.4\text{ g}}{49.8\text{ g}} = 1.11$, specific gravity of the salt solution. *Answer.*

56. Hydrometer Method. — A simple hydrometer is a rectangular stick weighted so that it will float upright in the liquid in which it is placed. A scale is marked along one side so that the depth to which the hydrometer sinks in a liquid can be noted. Such a hydrometer sinks much deeper in a light liquid, like gasoline, than it does in a heavy liquid like molasses. By testing with the hydrometer a number of liquids of different specific gravities, it is found that, like all floating bodies, the hydrometer sinks to a depth *inversely* proportional to the specific gravity of the liquid in which it is placed.

Hydrometers made of glass usually have a graduated paper scale inclosed in the hollow stem and a lower bulb weighted with mercury or small lead shot (Figure 86). For

liquids heavier than water, hydrometers have a scale reading *downward* from 1 to 2. The scale division of 1 marks the depth to which the hydrometer sinks in water, while in concentrated sulphuric acid it would only sink to about the 1.8 division. For liquids lighter than water, such as alcohol and ammonia water, hydrometers are adjusted to a scale reading *upward* from 1 to 0.7.

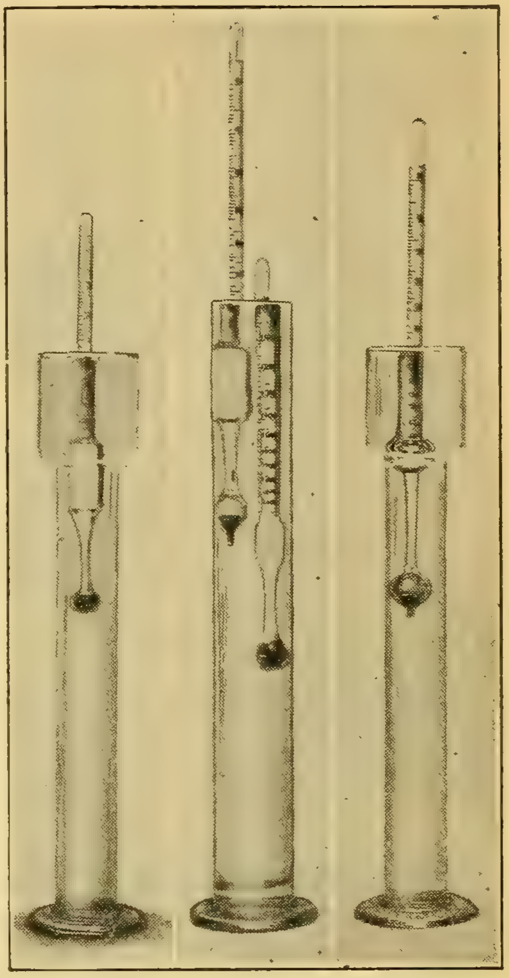


FIGURE 86. — HYDROMETERS.

The light hydrometer floats high in water, (center) and lower in alcohol, (left). The heavy hydrometer is low in water, but higher in sulphuric acid, (right).

EXPERIMENT 21. — By means of hydrometers determine the specific gravity of various liquids, such as water, a copper sulphate solution, a lubricating oil, kerosene, and the sulphuric acid solution used in a storage battery. *How does the specific gravity of a liquid affect the depth to which a hydrometer sinks? Why?*

57. Displacement Method. — A solid that sinks in a liquid displaces a volume of the liquid equal to its own volume, and the loss of the weight of the solid is equal to the weight of the liquid displaced (Archimedes' principle). If a body that is unaffected by the liquid to be tested is weighed (1) in air, (2) in water, and (3) in the liquid. The loss of weight in the liquid is the weight of the liquid displaced. The loss of weight in water is the weight of an equal volume of water. The weight of the displaced liquid divided by the weight of the equal volume of water gives the specific gravity.

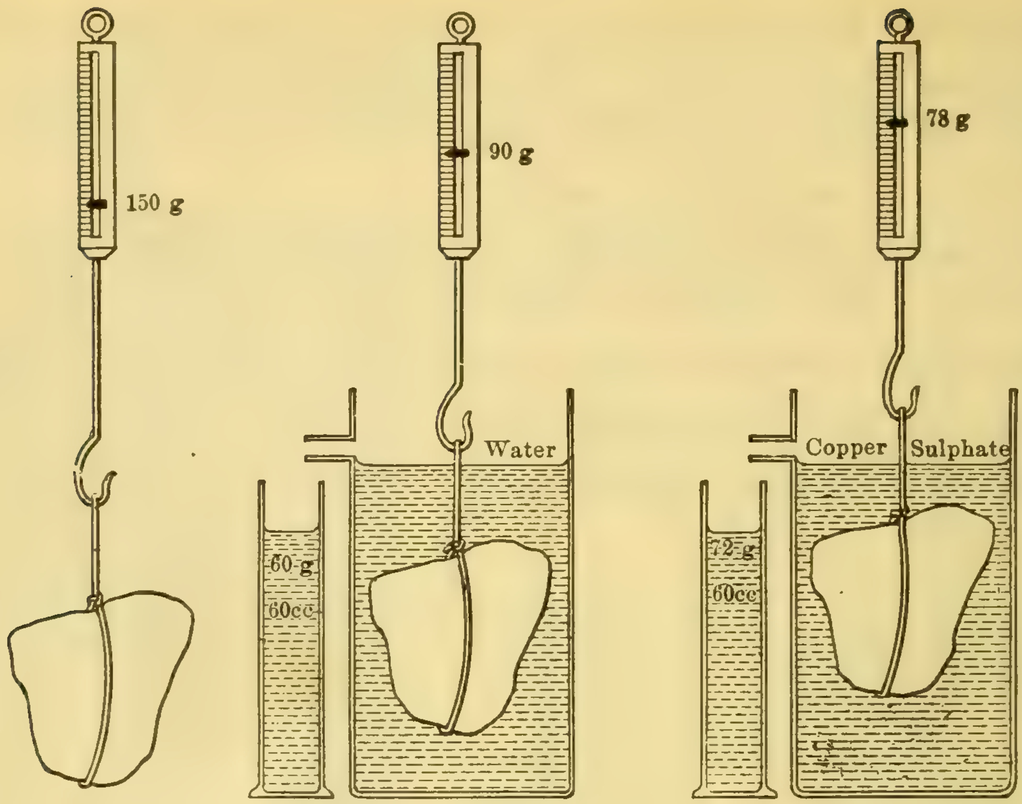


FIGURE 87. — DISPLACEMENT METHOD.

The stone displaces equal volumes of each liquid, and the quotient of the loss of weight in copper sulphate divided by the loss of weight in water is the specific gravity.

EXPERIMENT 22. — Weigh a piece of anthracite coal or of marble in air and then in copper sulphate solution. *How much does the coal lose in weight?* Weigh the coal in water. *What is the loss of weight in water? Compare the volumes of the copper sulphate solution and of the water displaced by the coal. What calculation will give the specific gravity of the copper sulphate solution? Result?* Check this calculated result with the specific gravity determined by a hydrometer.

By the displacement method for liquids:

$$\textit{Specific gravity} = \frac{\textit{weight of the liquid displaced by the body}}{\textit{wt of equal volume of water displaced by the body}}$$

Problem. A glass stopper weighs 61.1 g in air, 37.6 g in water, and 36.4 g in a solution of common salt. What is the specific gravity of the salt solution?

$61.1\text{ g} - 36.4\text{ g} = 24.7\text{ g}$, loss of weight of solid in salt solution.

$61.1\text{ g} - 37.6\text{ g} = 23.5\text{ g}$, loss of weight of solid in water.

$\frac{24.7\text{ g}}{23.5\text{ g}} = 1.05$, specific gravity of salt solution. *Answer.*

QUESTIONS

1. A stick of uniform section, loaded at one end, floats upright in water with 26 cm of its length submerged. What is the specific gravity of nitric acid, if 18 cm of the length of the stick is submerged when floating in the acid?

2. How is the weight of water in a labeled specific gravity bottle obtained?

3. A bottle with a capacity of 150 cm^3 holds 2040 g of mercury. What is the specific gravity of the mercury?

4. An empty specific gravity bottle weighs 20 g. Filled with syrup the weight is 35 g; with water 32 g. Find the specific gravity of the syrup.

5. A specific gravity bottle that weighs 30 g when empty, weighs 80 g when filled with water and 90 g when filled with a solution of copper sulphate. Calculate the specific gravity of the copper sulphate solution.

6. A specific gravity bottle weighs 60 g when empty, 85 g filled with water, and 82.5 g filled with oil of peppermint. What is the specific gravity of the oil of peppermint?

7. A glass stopper weighs 27 g in air, 17 g in water, and 19 g in alcohol. What is the specific gravity of the alcohol?

8. A body when weighed in water loses 9 lbs, and loses 7.1 lbs in kerosene. Find the specific gravity of the kerosene.

9. A solid glass ornament weighs 40 g in air, 25 g in water, and 20 g in a certain acid. What is the specific gravity of the acid?

10. A stone weighs 100 g in air, 70 g in water, and 65 g in a liquid. Calculate the specific gravity of the stone and of the liquid.

11. A 50-gram brass weight weighs 44.12 g in water and 45.29 g in wood alcohol. Find the specific gravity (*a*) of the brass; (*b*) of the wood alcohol.

12. A lead bar weighing 24 lbs floats in mercury (sp gr 13.6). If the lead has a specific gravity of 11.3, what will be the apparent loss of weight in mercury? What fractional part of the lead bar will be submerged?

58. Practical Uses of Hydrometers. — The bottle method, or a slight modification of it, is a very accurate way of determining the specific gravity of liquids. For practical purposes, however, the more rapid, but less accurate, hydrometer method is generally used. This instrument is important in the manufacture of acids, in the separation of the various oils obtained in the distillation of crude petroleum, and in many other industries. It finds frequent employment in the testing of the sulphuric acid solutions used in the lead storage batteries of automobiles (Figure 88). Since specific gravity is often an indication of purity, the hydrometer is a quick means of testing olive oil and many other oils. Milk inspectors use a special form, known as the *lactometer*, as a ready method of testing milk for water adulteration. The sugar and the alcohol industries have

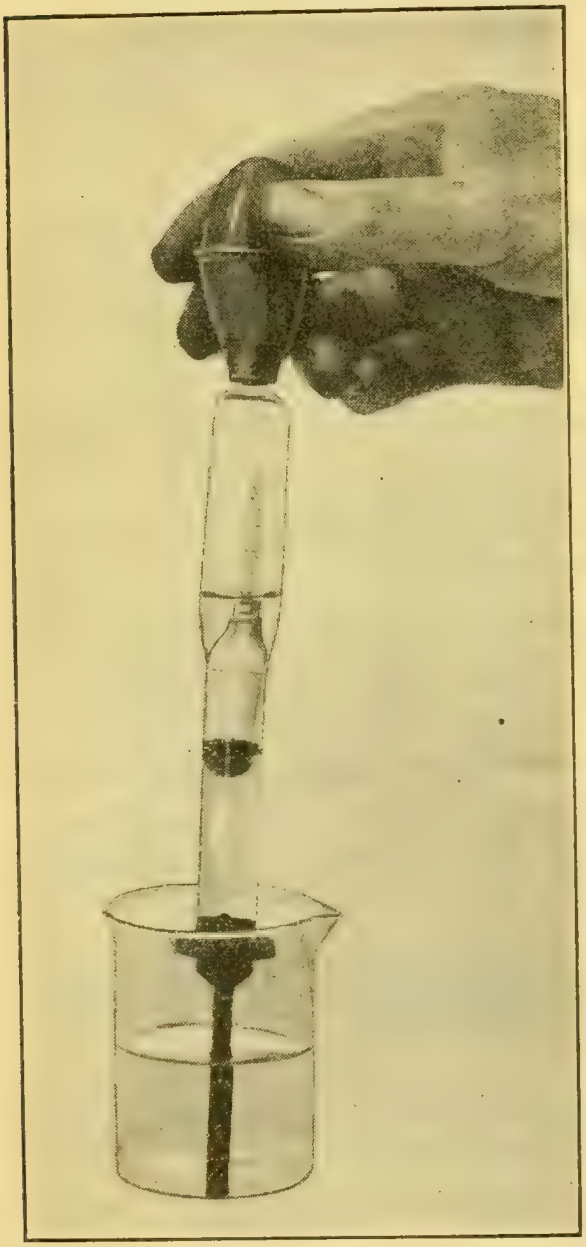


FIGURE 88. — A BATTERY TESTER.

The battery acid is drawn up into the tube, and the specific gravity shown by the hydrometer indicates the condition of the battery.

hydrometers with scales adapted to their special needs. The scales of the special hydrometers are often arbitrarily numbered to correspond to certain percentage strengths of solutions.

59. Density. — Iron is heavier than tin and lead is heavier than iron. By this we mean that, if we take equal-sized pieces of the three materials (Figure 89), the lead has the greatest weight. So we conclude that there are more pounds per cubic foot (or grams per cubic centimeter) of lead than of iron or of tin. That is, the lead has the greatest *density*, for *density is the mass per unit volume of a substance.*

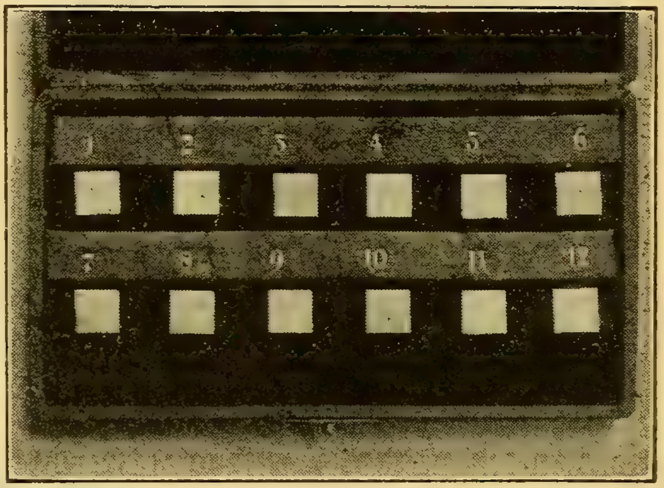


FIGURE 89. — DENSITY CUBES.

Centimeter cubes of 12 metals. The density of each is directly determined by weighing it.

In the English system of weights and measures, the pound is the unit for measuring mass, and a cubic foot is the unit of volume. Thus, water has an approximate density of 62.5 pounds per cubic foot. In metric units, its density is 1 gram per cubic centimeter. Aluminum has a density per cubic foot of 162 pounds (162 lbs/ft^3); iron, about 500 pounds; copper, 550 pounds; silver, 650 pounds; gold, 1200 pounds; platinum, 1340 pounds; cork, 15.6 pounds; and ice, 57.3 pounds.

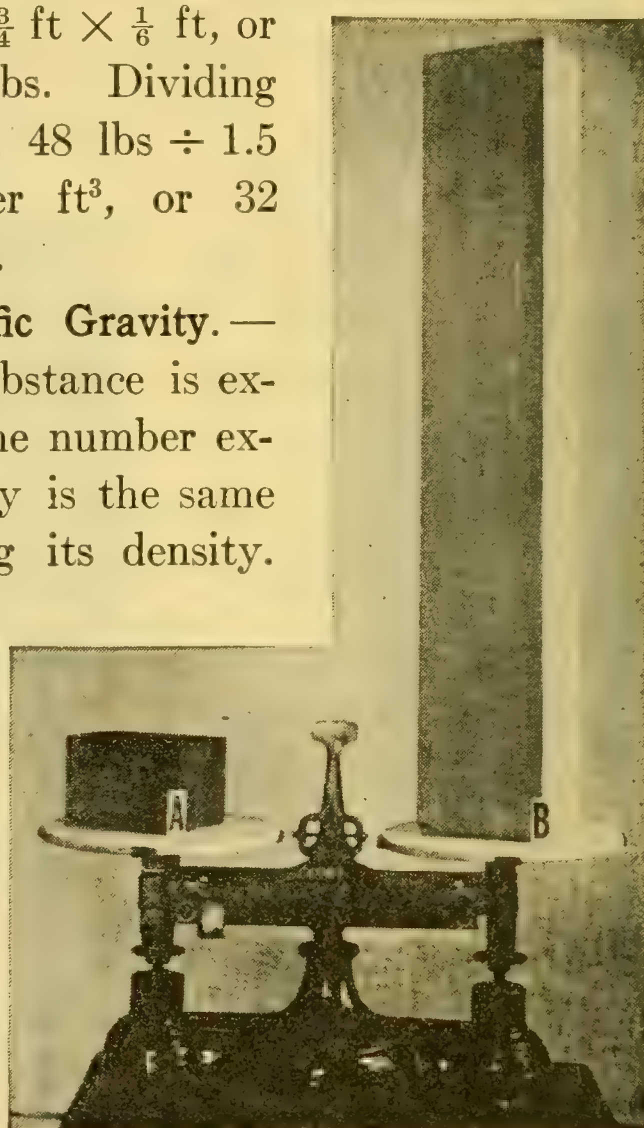
The term "density" applies to gases as well as to liquids and solids. Chlorine has a greater density than carbon dioxide, while the latter is much denser than hydrogen. Hydrogen has a density of 0.00009 gram per cubic centimeter.

To find the density of a substance, we determine its mass by

weighing it and then dividing this mass by the volume found by some method of measurement.

Problem. Find the density of the wood in a plank that is 12 ft long, 9 in wide, and 2 in thick, and which weighs 48 lbs.

The volume is 12 ft $\times \frac{3}{4}$ ft $\times \frac{1}{6}$ ft, or 1.5 ft^3. The mass is 48 lbs. Dividing the mass by the volume, 48 lbs $\div$ 1.5 ft^3 = 32 lbs of wood per ft^3, or 32 lbs / ft^3, density. *Answer.*



Courtesy Henry Disston & Sons.

FIGURE 90. — EQUAL WEIGHTS OF IRONWOOD AND BALSA WOOD.

A, Ironwood, 70.5 lb per ft^3; *B*, Balsa, 7.3 lb. per ft^3.

60. Density and Specific Gravity. — When the density of a substance is expressed in metric units, the number expressing its specific gravity is the same as the number expressing its density. This equivalence has led to much looseness in the use of the term "density," when specific gravity is really meant. *Specific gravity* is the number of times a substance is as heavy as an equal volume of water or air, taken as a standard. *Density* is expressed without requiring the use of another substance as a standard, and should always be stated as a certain mass per unit volume. The specific gravity of sulphur is 2 (an abstract number), while its density is 2 grams per cubic centimeter. Wrought iron has a specific gravity of 7.8; and a density

of 7.8 grams per cubic centimeter (metric system) or 487 pounds per cubic foot (English system). One can avoid confusion in the use of the two terms by thinking of specific gravity as relative density, needing simply a number for its expression, while density itself must be stated in units of mass per unit of volume.

SUMMARY

The **specific gravity** of a solid or of a liquid is the number of times a certain volume of that substance is as heavy as an equal volume of water.

Archimedes' principle is of aid in finding the specific gravity of irregular pieces of either light or heavy solids that are insoluble in water, since this principle gives a means of finding the weight of the "equal volume of water." The hydrometer and displacement methods are also based on this principle.

Formulas for Specific Gravity Methods for Solids.

(*a*) Geometrical Solids: (*b*) Irregular Solids Heavier Than Water: (*c*) Irregular Solids Lighter Than Water:

$$\text{Specific gravity} = \frac{\text{weight of solid}}{\text{weight of equal volume of water}}$$

(*d*) Geometrical Bodies Lighter Than Water:

A floating body sinks until it displaces a volume of water that is the same fraction of the volume of the body as the number used to express the specific gravity. Determine the fraction representing the immersed portion.

Specific Gravity of Liquids.

(*a*) Hydrometer Method:

A hydrometer sinks to a depth that is inversely proportional to the specific gravity of the liquid in which it is placed. The specific gravity of the liquid tested is read as the scale division marking the liquid level on the stem.

(*b*) Bottle Method:

$$\text{Specific gravity} = \frac{\text{weight of a bottleful of liquid}}{\text{weight of a bottleful of water}}$$

(*a*) Displacement Method:

$$\text{Specific gravity} = \frac{\text{weight of the liquid displaced by a body}}{\text{wt of equal volume of water displaced by the body}}$$

Hydrometers have many practical uses, since they afford a rapid and fairly accurate method for determining the specific gravity of liquids, such as oils, acids, and many solutions.

Density is the mass per unit volume of a substance. The density of solids and of liquids is usually expressed in pounds per cubic foot or grams per cubic centimeter. The density of gases is stated in grams per cubic centimeter or grams per liter.

Density is found by weighing a substance to get the mass, and then dividing this mass by the volume found by some method of measurement.

Density should not be the term used when specific gravity is meant. The latter is the weight of a substance compared with the weight of an equal volume of another substance taken as the standard. Density is the mass per unit volume of a substance.

EXERCISES

1. State the standards used respectively for the specific gravity of solids, liquids, and gases.

2. What is meant by 7.3 as the specific gravity of tin? By 13.6 as the specific gravity of mercury? By 1.1 as the specific gravity of oxygen?

3. State Archimedes' principle. How is it used in finding specific gravities?

4. State the weights of two different unit volumes of water. How is the work in some specific gravity determinations shortened by knowing these weights?

5. In the *sinker method* for finding the specific gravity of an irregular solid lighter than water, state (*a*) the reason for the use of the sinker; (*b*) what weighings must be made; (*c*) how the weight of the equal volume of water is found and why this is so; and (*d*) the formula for the final calculation.

6. Describe the construction of a wooden hydrometer and state how it is used in determining the specific gravity of a liquid.

7. State how far floating bodies sink in water.

8. Describe the hydrometer method of finding the specific gravity of a liquid. How does the depth to which the hydrometer sinks compare with the specific gravity of the liquid?

9. Why is a glass hydrometer weighted at the bottom? Make drawings of hydrometers showing the scale with the divisions labeled for (*a*) heavy liquids; (*b*) light liquids.

10. Describe a method for determining the specific gravity of a heavy solid. State clearly the quantities that must be determined and how they are used to calculate the specific gravity.

11. Which is the easiest method of determining specific gravity of liquids? What is the commonest method? Which is the most accurate method?

12. Describe the bottle method of finding the specific gravity of a liquid. Supply the necessary data and calculate the specific gravity of a liquid.

13. Describe the displacement method of finding the specific gravity of a liquid. Supply data and calculate the specific gravity of a liquid.

14. What is indicated concerning specific gravities by the fact that iron floats about 0.6 submerged on mercury?

15. Is the average specific gravity of a floating iron ship greater or less than 1? How does this change if the ship leaks?

16. Define *density.* In what different units is density commonly expressed? Calculate the density of iron in tons per cubic yard.

17. Find the density of carbon dioxide, if 360 cm^3 weigh 0.71 g.

18. Why is water taken as the specific gravity standard for solids and liquids?

19. A body loses 40 g when weighed in water. (*a*) What is the weight of an equal volume of water? (*b*) If the body weighs 200 g in air, how many times is it as heavy as an equal volume of water? (*c*) What is its specific gravity? (*d*) Give its density in the metric system. (*e*) Calculate its density in the English system.

20. A body weighs 800 lbs in air and 600 lbs in water. Find (*a*) the weight of the water displaced; (*b*) the specific gravity of the body; (*c*) its volume; (*d*) its density in pounds and cubic feet.

21. Make a problem which will work out to give the correct specific gravity of copper. Show how your problem should be solved. (See table in the Appendix.)

22. Samples of two grades of iron of the same size weigh respectively 1531 g and 1559.6 g in air and 1331 g and 1359.6 g in water. Find the specific gravity of each, the volume of each, and identify each by reference to the table in the Appendix.

CHAPTER VII

THE ATMOSPHERE AND ITS PRESSURE

61. Weight of the Air. — There is nothing in the evidence of our senses that shows us directly that air has weight. Air, however, can be pumped like water, which we know does have weight. Thus air is pumped into a pneumatic tire and is pumped out in making an incandescent lamp. We do

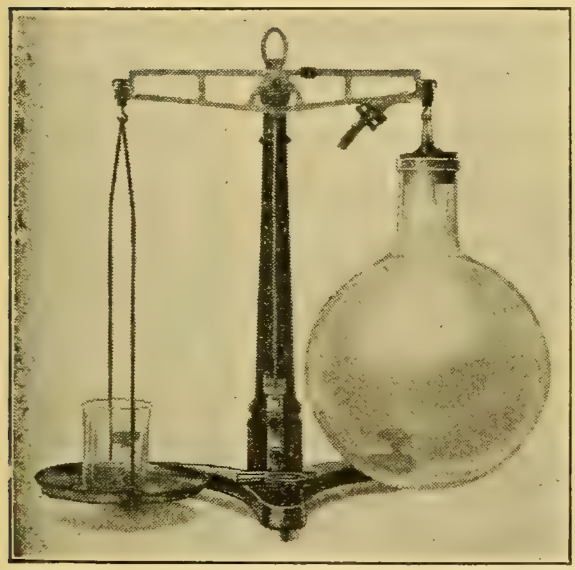


FIGURE 91 *a*. — A BALANCED FLASK OF AIR.

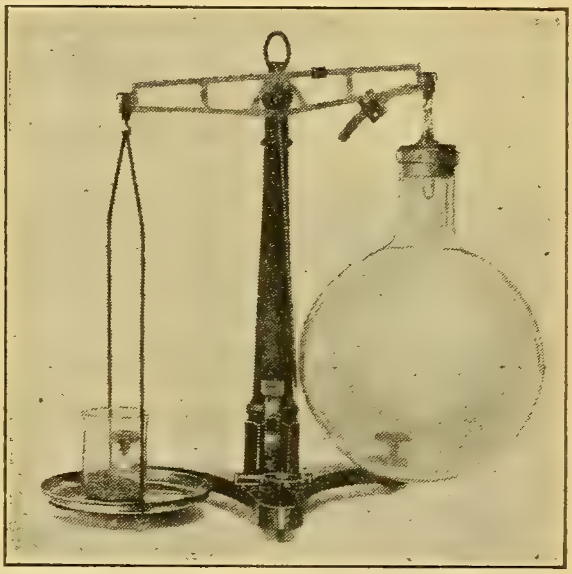


FIGURE 91 *b*. — SOME AIR HAS BEEN PUMPED OUT.

not ordinarily think of air as having weight, simply because we are accustomed to living at the bottom of the great ocean of air and are constructed to sustain its weight. The fact that air has weight is easily shown by a simple experiment.

EXPERIMENT 23. — Counterpoise an empty glass flask on a balance (Figure 91, *a*). Then exhaust the air from the flask by means of an air pump, and close the screw compressor. Remove the tube connected to the air pump, and note which side of the balance is now heavier (Figure 91, *b*). *What does the decrease in the weight of the flask show?*

If we knew the capacity of the flask in the experiment, we could find the weight of a definite volume of air and calculate the weight of a volume of any size. Similar experiments show that air weighs about $1\frac{1}{4}$ oz. per ft^3, or 12 ft^3 weigh a pound. The air in a schoolroom $28 \times 22 \times 10$ ft weighs over 500 lbs. A liter of air at 0° C and 760 mm pressure (§ 68) weighs 1.29 g.

62. Pressure of the Atmosphere. — Since air has weight, it must exert pressure on any surface that it touches. This pressure is exerted equally in all directions. Everywhere on the earth this atmospheric pressure must be sustained. The air makes its way through cracks and crevices into even the most tightly closed buildings, and the pressure inside changes with that outside. The force of the air on a horizontal surface is equal to the weight of all the air directly over that surface. If the surface is not horizontal, the air still presses *perpendicularly* against it with a force equal to the weight of all the air that would rest on it, if it were turned into a horizontal position. That the atmosphere exerts great pressure is shown by the following experiments.

FIGURE 92.

EXPERIMENT 24. — Fill a glass cylinder with water to the brim. Wet a piece of cardboard and lay it carefully on top of the water in the cylinder. Hold the card, invert the cylinder slowly, and then remove the hand (Figure 92). *Why does not the card fall?*

EXPERIMENT 25. — Put a little water in an ordinary kerosene can which has a rubber tube slipped over the spout (Figure 93). Then screw the top down tight. Heat the bottom of the can with a burner so as to change the water into steam, which will push most of the air out of the can. Then close the screw compressor on the rubber tube, and stop the heating. Pour cold water over the can. As the cooling proceeds,

the steam condenses to water, which occupies less than a thousandth of the room taken by the steam in the can. Hence there is hardly any pressure exerted on the inner walls of the can. *What pressure accounts for the crushing of the can?*

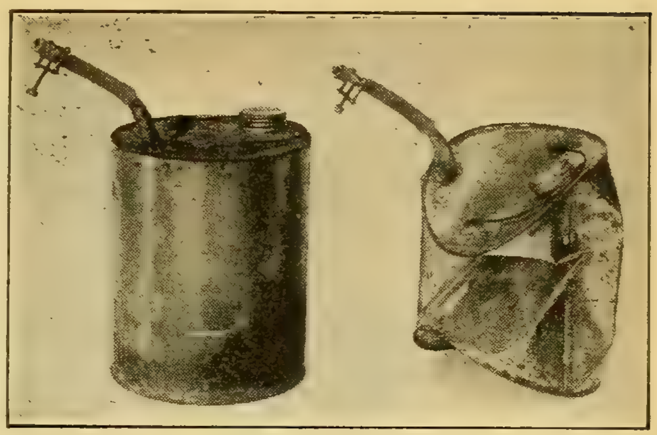


FIGURE 93. — BEFORE AND AFTER AIR HAS BEEN REMOVED FROM THE INTERIOR OF THE CAN.

63. Torricelli's Experiment. — The natural philosophers in the Middle Ages accounted for the rise of water in a pump by saying "Nature abhors a vacuum." The Grand Duke of Tuscany found to his surprise that he could not pump water for his fountains from a well about 50 feet deep. Galileo (1564–1642), investigating the matter for him, found that the water rose about 32 feet in the pump tubes, and is said to have remarked that "Nature does not seem to abhor a vacuum above 32 feet." Galileo had previously suggested that air had weight and this idea he gave to his friend and disciple, Torricelli (1608–1647). The latter reasoned that the 32 feet of water in the pump was held up by the weight of a column of atmosphere. From a famous experiment devised by Torricelli, the world gained its idea of atmospheric pressure. We can readily repeat this experiment as follows.

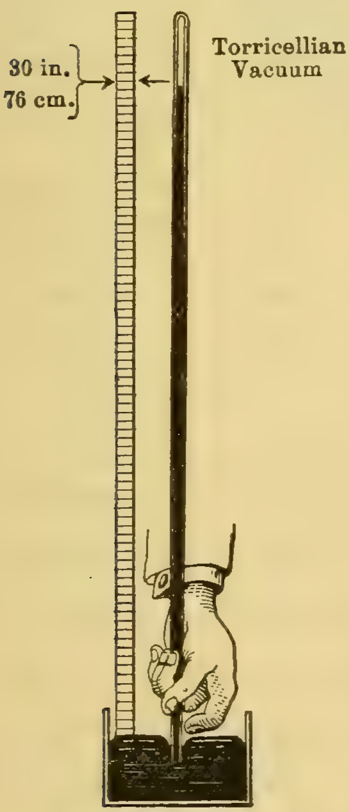


FIGURE 94.

EXPERIMENT 26. — Take a glass tube about 3 feet long that is sealed at one end and filled with mercury. Closing the open end with the

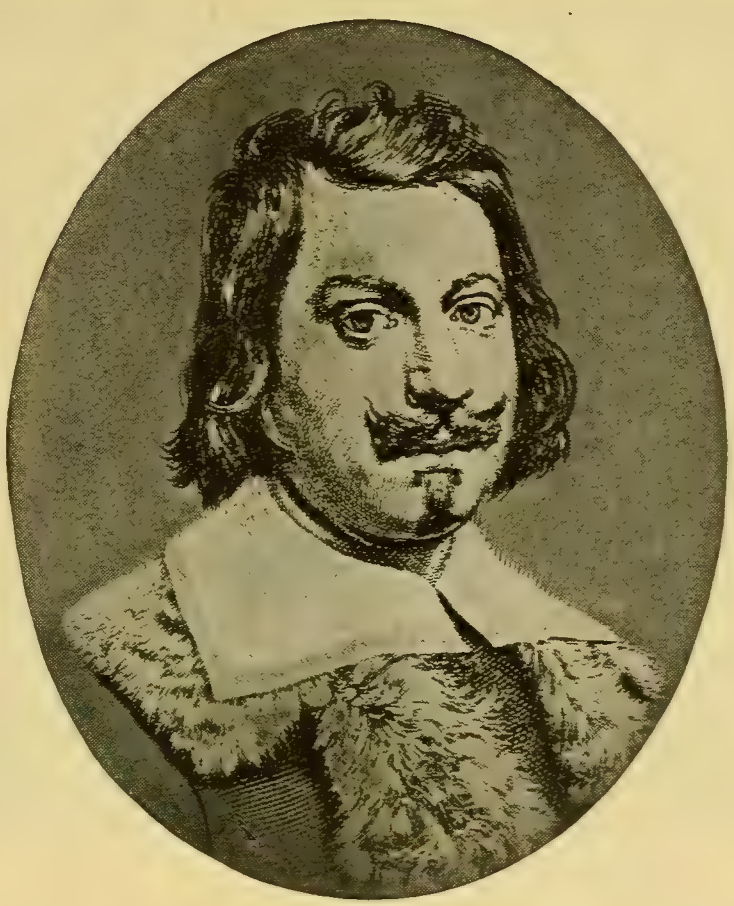
thumb, slowly invert the filled tube and put the lower end below the surface of some mercury in a dish (Figure 94). On removing the thumb, the mercury in the tube sinks till it stands about 30 inches above the level of the mercury in the dish. *Why does it not fall farther?* The empty space left at the top of the tube is known to this day as the *Torricellian vacuum.*

The pressure of the atmosphere on the surface of the mercury in the dish, transmitted to the bottom of the tube in accordance with Pascal's Law (§ 41), is able to counterbalance the downward pressure due to the weight of a column of mercury about 30 inches high.

This pressure, Torricelli reasoned, is exerted by the atmosphere on every surface. Defined in terms of unit area, it is equal to about 14.7 pounds per in^2 or a kilogram per cm^2, when the pressure of the atmosphere holds up a column of mercury exactly 30 inches high (or very nearly 76 cm).

As mercury is 13.6 times as heavy as water, the atmosphere should be able to hold up a column of water 13.6×30 inches, which equals 34 feet. This has been confirmed by experiment. Water vapor, forming above the column, may somewhat reduce its height.

64. The Magdeburg Hemispheres. — The great pressure of the atmosphere was strikingly shown in the seventeenth century by Otto von Guericke, the burgomaster of Magdeburg. He made two hollow iron hemispheres about two feet in diameter with smooth rims that fitted tightly together. When the two rims were fitted into each other and the air exhausted from the hollow globe thus formed, eight teams of horses pulling on the hemispheres were needed to pull them apart (Figure 95). This historical experiment was performed in the presence of the German emperor, Alexander III, and the Reichstag.



Evangelista Torricelli (1608–1647) was a careful student of Galileo's writings. At Galileo's suggestion, Torricelli investigated the failure of a lift pump to raise water from a depth of more than about 30 feet below its piston valve. Torricelli explained this height as being that of a column of water whose downward pressure equals the atmospheric pressure against it. Substituting mercury for water, he found, as he expected, that a column only 30 inches long was supported. This was the first barometer. Variations of the barometer with changes in altitude and weather were studied by Pascal, Descartes, Huygens, and many others.

FIGURE 95.—THE MAGDEBURG EXPERIMENT.

The details of the hemispheres are shown at the top.

65. The Mercury Barometer. — Torricelli's apparatus is used to-day in slightly modified forms as the barometer, the instrument for measuring atmospheric pressure. The *barometer* is essentially a straight glass tube, closed at one end, which has been filled with mercury and placed upright with its open end beneath the surface of mercury in a reservoir. Even in settled weather, the atmospheric pressure varies slightly, so the mercury column of the barometer constantly changes in length, to balance the changing pressure.

In Fortin's cistern barometer (Figure 96), any change in level of mercury in the cistern, caused by the change in length of the mercury in the tube, is counteracted by giving to the mercury cistern a movable bottom. This is of leather,

and can be adjusted by a screw device so as to bring the mercury always to the same level in the cistern. The height of the mercury column in the tube is measured from this level.

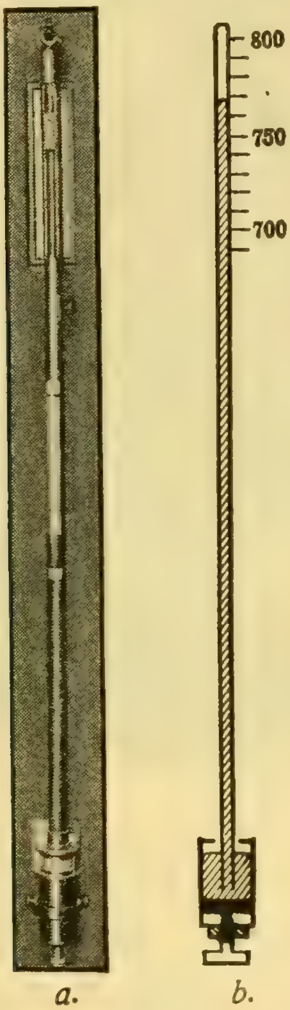


FIGURE 96. — BAROMETER.

a, External view; *b*, Section. The movable bottom and adjusting screw are shown. An index point in the cistern shows when the mercury level is at the 0 of the scale.

To measure the slight variations in pressure, most laboratory barometers have a scale reading in millimeters. The following experiment confirms the belief that the barometer column is sustained by atmospheric pressure.

FIGURE 97.

EXPERIMENT 27. — Make a simple barometer, in which the cistern is a small wide-mouth bottle, provided with a 2-hole stopper (Figure 97). Through one hole pass the barometer tube and through the other a bent glass tube, which is connected to an air pump. As we pump the air out, the mercury falls. *Why?* When the pump has exhausted all the air that it can, the mercury in the tube stands but a short height above the mercury level in the bottle. *What does this show about the pressure inside the bottle?* If we admit air to the bottle, the mercury column rises. *Why? What is shown by the rapid rise of the mercury when the air valve is opened wide?*

QUESTIONS

1. Why is the weight of the air not ordinarily apparent to us?

2. Describe an experiment that proves air has weight.

3. On what does the atmosphere exert its pressure? In what direction is it exerted?

4. How much pressure is sustained by every surface in contact with the air?

5. A piece of cardboard is placed over the top of a tumbler of water. Why does not the water fall out when the tumbler is inverted?

6. Explain the crushing of a tightly closed kerosene can that is allowed to cool after being filled with steam.

7. What led Galileo to investigate the depth from which water could be raised by a pump? What did he learn?

8. How did Torricelli explain the lifting of water by a pump?

9. State how you would make a mercury barometer. What name is given to the space above the mercury in the tube?

10. What holds up the mercury column in a barometer? What is the height of mercury under usual conditions?

11. State the normal pressure of the atmosphere on a square inch and on a square centimeter.

12. Account for daily variations in the barometer readings.

13. Describe an experiment with a barometer, a bottle, and an air pump that shows the barometric column is sustained by atmospheric pressure.

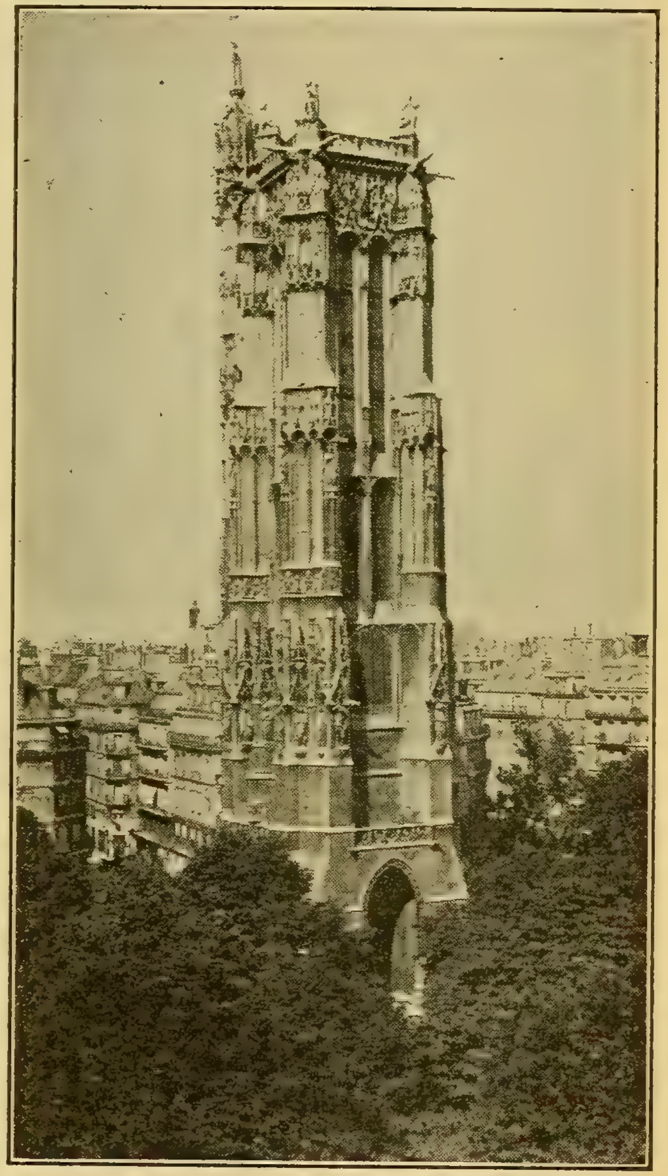


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FIGURE 98. — TOUR ST. JACQUES, TO THE TOP OF WHICH PASCAL CARRIED HIS BAROMETER.

66. The Barometer and Altitude. — When the results of Torricelli's experiment became known in France, Pascal said that the atmospheric pressure at the top of a

mountain must be less than at the sea level, since the amount of overlying air decreases as one ascends. As Paris lacked a mountain near at hand, Pascal had to content himself with the testing of his theory by carrying a Torricellian tube to the top of a high tower in Paris (Figure 98). To get further confirmation, he wrote to his brother-in-law in the southern part of France, asking him to repeat the experiment on the Puy de Dome, which had an elevation of over three thousand feet. This experiment showed that the column of mercury was nearly 8 cm shorter on the mountain top than at Paris.

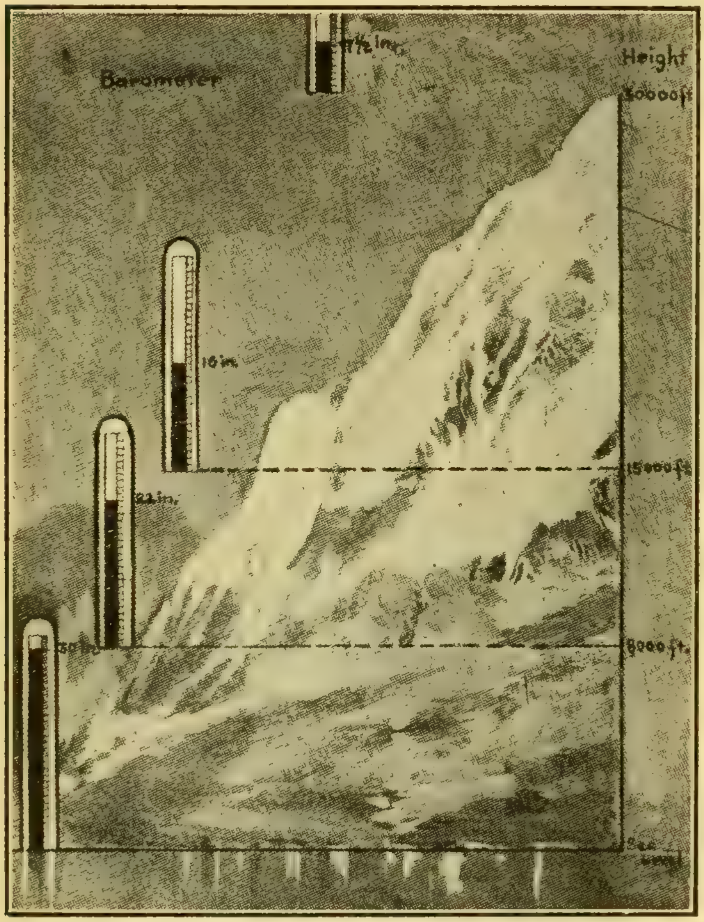


FIGURE 99. — ALTITUDE AND ATMOSPHERIC PRESSURE.

An idealized view of a mountain rising from the sea to the height of Mt. Everest. The barometer heights correspond to the altitudes shown at the right.

The decrease of the barometer reading with the altitude gives a means of determining the latter. Near the sea level, there is a decrease of about 0.1 inch for every 90 feet of ascent. This rate of decrease is not maintained on reaching high levels, owing to the lessening density of the air. Tables, however, have been made so as to allow for the ascending variations and the necessary temperature corrections. Thus the altitude of a

place can be determined by the difference in the pressures read at the same time at that place and at a place of known altitude (Figure 99). The barometer near the pilot of an airplane or dirigible is indispensable in the navigation of the air, for it is the only reliable indicator of altitude at hand.

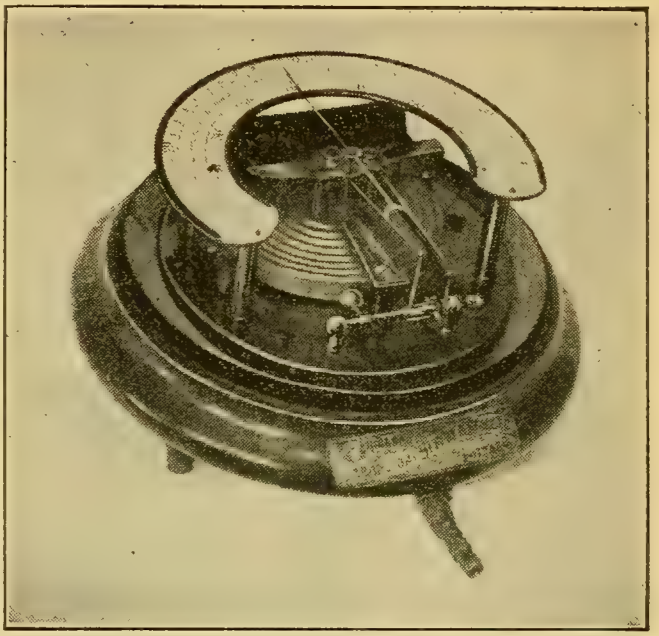


FIGURE 100.—A DEMONSTRATION ANEROID BAROMETER.

67. Aneroid Barometer.—The mercury barometer is inconvenient for measuring altitudes on account of its length and the use of a liquid. The aneroid barometer (Figure 100), as the derivation of its name indicates, has no liquid. Since it may change in accuracy, it has to be compared from time to time with a mercury barometer. A good aneroid barometer is so sensitive, however, that it will show a difference in pressure between the top of a table and the floor.

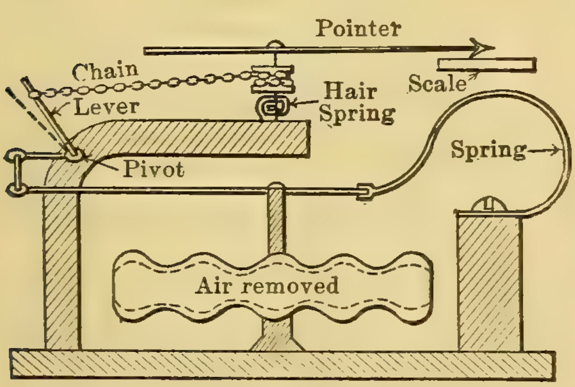


FIGURE 101.—SECTIONAL VIEW OF AN ANEROID.

Increased pressure causes the box and lever to take the position shown by dotted lines. The pointer will then swing outward.

The aneroid barometer has a metallic box with a thin cover of slight curvature (Figure 101). The air has been partly exhausted from this box. Hence slight changes in the atmospheric pressure alter the curvature of the cover. This com-

municates its motion to a system of levers that move a pointer on a circular scale (Figure 101). The scale divisions represent inches or centimeters, corresponding to the readings on a mercury barometer. This type of barometer can be made very small and yet retain its accuracy (Figure 102). Mountain climbers use a size that can be strapped on like a wrist watch.

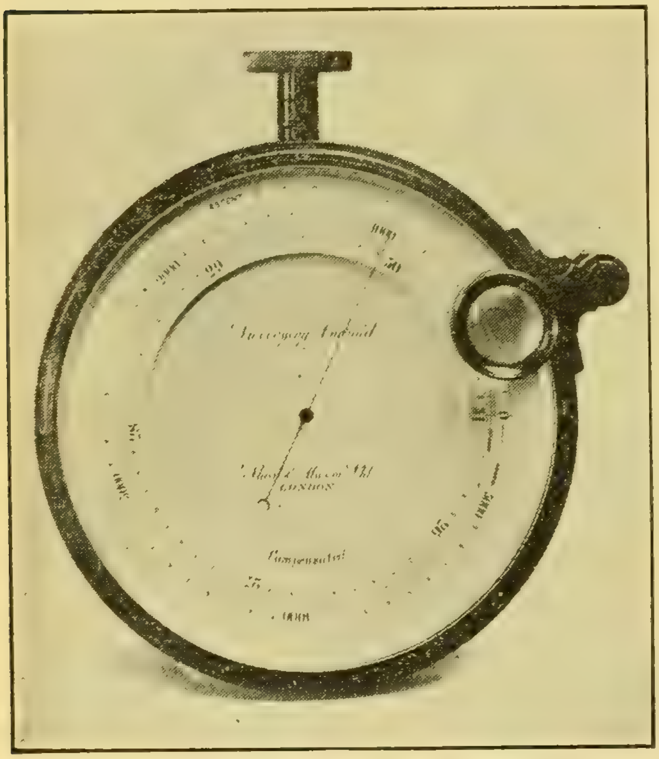


FIGURE 102. — SURVEYING ANEROID.

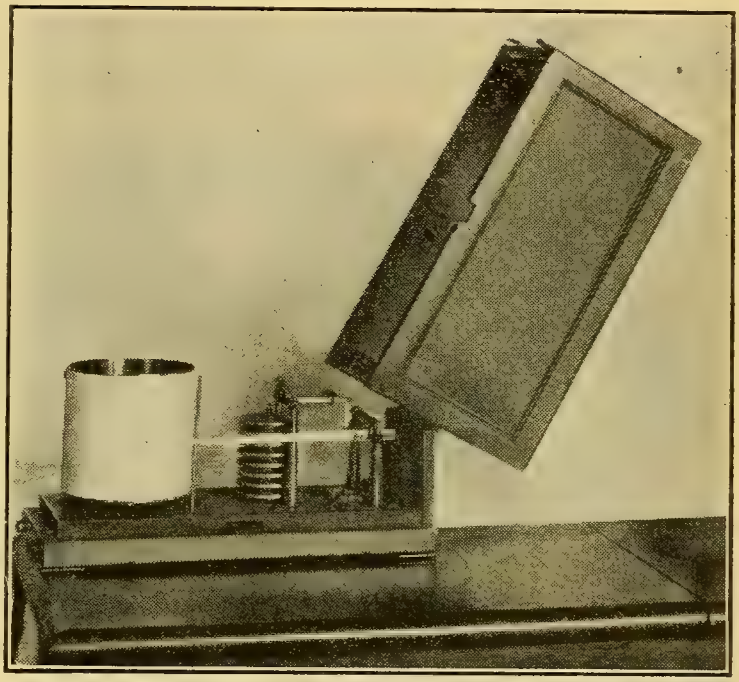
This is provided with a direct reading scale of feet, and will show the difference in pressure between the floor and a table top.

68. Normal Atmospheric Pressure. — Scientists take 76 cm of mercury as the normal atmospheric pressure on a cm^2 of surface *at sea level,* for this has been found to be the value obtained by averaging the barometer readings at sea level through a long period of time. Our Weather Bureau takes 30 inches of mercury for the normal atmospheric pressure per in^2, steam engineers use 14.7 pounds per in^2 as their normal, which is also employed for air and other gases compressed in pipes and tanks for industrial use. In many scientific experiments such as those dealing with the liquefaction of gases, normal pressure is simply called *one atmosphere.* In pump calculations, 34 feet of water is the normal atmospheric pressure.

It is interesting to note that none of these normal atmospheric pressures is exactly equal to any of the others. The

standard figures taken for the various purposes should be remembered as being only approximately equal to one another.

69. Height of the Atmosphere. — The height of the atmosphere has been a matter of interesting speculation, and has led to many daring attempts to explore the upper regions of the air by means of passenger balloons.



Courtesy U. S. Weather Bureau.

FIGURE 103. — BAROGRAPH.

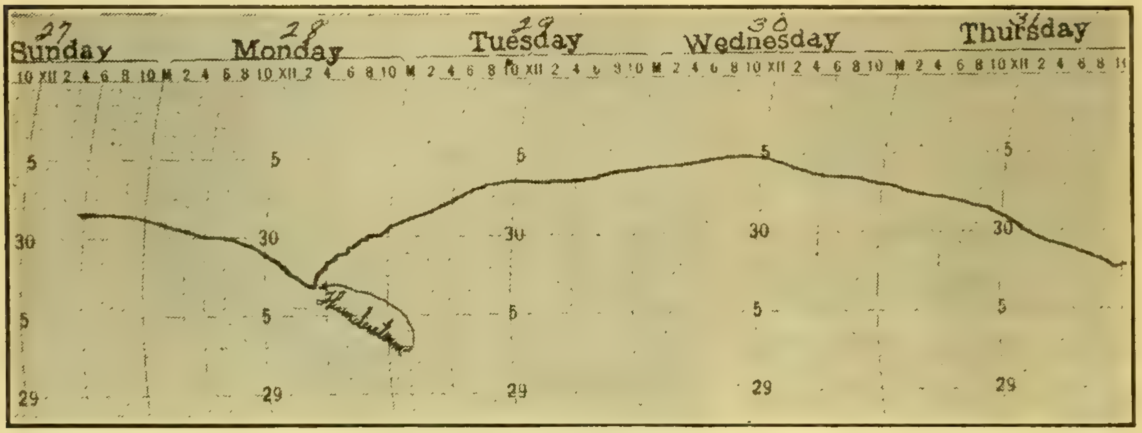
By using a number of aneroid boxes and a long lever, terminating in a pen, a continuous record is made on paper on the drum driven by clock-work.

A modern method of exploration is to send up self-registering thermometers and barometers (Figure 103) in small balloons which burst on reaching the greatly diminished pressures of high altitudes. The instruments descend safely in parachutes that open when the balloon starts to fall after bursting. By this method in 1910, a United States government observer in South Dakota explored a height of almost 19 miles.

At 30 miles, the pressure is calculated to be about $\frac{5}{1000}$ of an inch; at 50 miles, a limiting height sometimes given for the atmosphere, the air would be so excessively thin that there would be no indication of pressure. Yet the air must extend beyond this, since meteors, known to enter our gaseous envelope 100 miles above the earth, are set on fire by compressing the air in front of them. We can only say that the

atmosphere at these extreme heights exists in a state of great rarity, so rare indeed that we cannot even imagine the great isolation of the individual air particles.

70. Barometer and the Weather.—The barometer indicates from day to day the changes in the atmospheric pressure and therefore aids in foretelling the weather. A *falling* barometer usually indicates the approach of a storm (Figure 104), particularly if the drop is sudden, as sea captains well know. A *rising* barometer usually heralds the coming of *fair* weather, while a *continued high* barometer means *settled fair* weather.



Courtesy U. S. Weather Bureau.

FIGURE 104.—BAROGRAPH RECORD.

Note the falling barometer before the thunderstorm and the rise of pressure following it.

The changes in the atmospheric pressure are observed daily by the Weather Bureau stations all over the United States. The readings are telegraphed to other stations, and after being corrected for altitude variations, are recorded on weather maps, on which the places of equal pressure are connected by lines known as *isobars* (Figure 105). The completed isobars are irregular curves, which may surround either an area of low pressure or of high pressure.

The reason for the high and low pressure areas is not

certainly known, but the results are most noticeable. Air starting from high pressure area toward low pressure area is given a rotary motion which is counterclockwise in the Northern Hemisphere. Around a low pressure area there

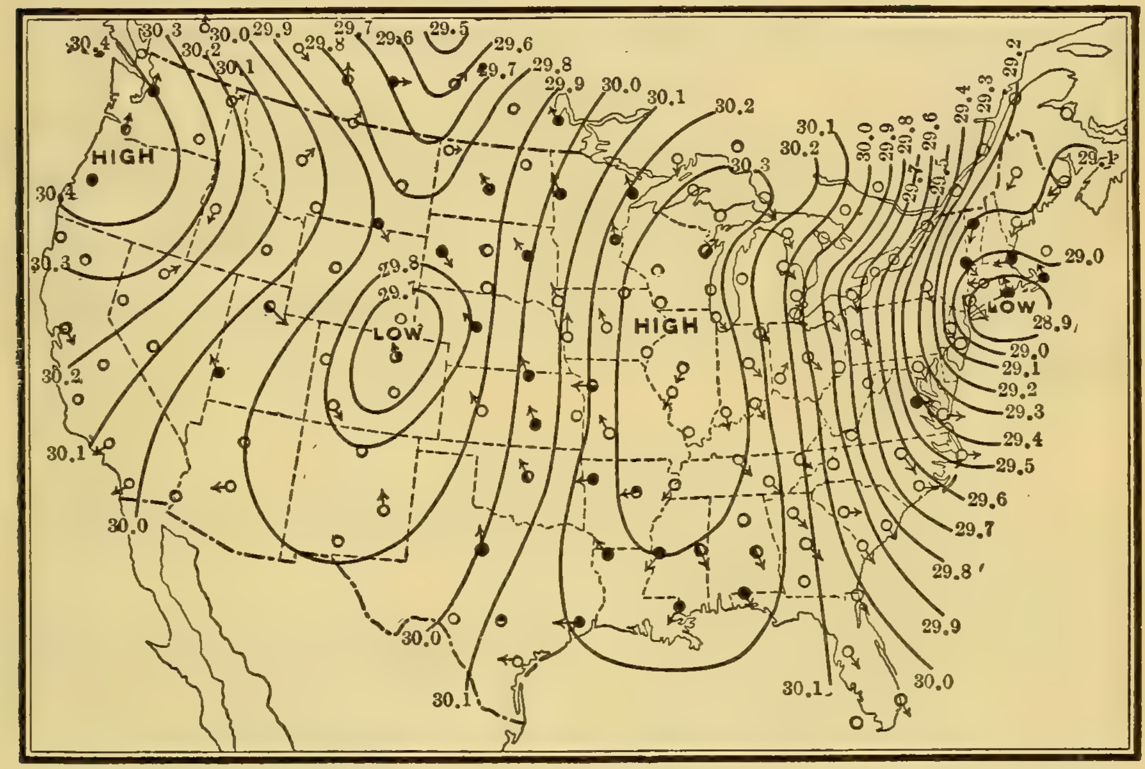


FIGURE 105.—A WEATHER MAP.

Arrows show the directions of the winds toward lows and away from highs. Solid circles show clouds and open ones fair weather.

may be, therefore, a gigantic whirling storm sometimes 1000 miles across. This storm is called a *cyclone.*

Cyclones usually originate in the Northwest and travel eastward by the Great Lakes and the St. Lawrence valley, like enormous eddies in the great stream of the prevailing westerlies (§ 117). They travel 500 miles or more in a day and distribute rainfall over the eastern portion of the country, which would otherwise be rainless. They are attended by falling barometer, easterly winds shifting toward the west as the storm passes, heavy rain or snow, and

higher temperature. Alternating with the cyclones, come the *anticyclones* around the high pressure area. They are attended by a rising barometer, westerly winds, colder weather, and clearing skies. An advancing area of high pressure brings the chilly air from the Northwest in the winter, causing the "cold waves." The winds about a "high" move in a clockwise direction.

The term "cyclone" is often wrongly applied to the *tornado*, which sweeps over a limited area causing great destruction in its path. Tornadoes are caused by the overheating of a locality and an overturning of the resulting convectional currents (§ 111).

QUESTIONS

1. What did Pascal do and prove when he heard of Torricelli's experiment with a mercury column?

2. What is the rate of decrease in the barometer reading as we ascend moderate elevations from sea level?

3. How may the altitude of a place be determined with the aid of a barometer?

4. Describe the construction and operation of an *aneroid barometer*.

5. What advantages has an aneroid barometer over a mercury barometer?

6. Define *normal* atmospheric pressure in terms used respectively by scientists, steam engineers, and officers of weather bureaus.

7. Describe a modern method of exploring the pressures in the upper regions of the air.

8. How far does the atmosphere extend above the earth? What are the reasons for thinking so?

Applications of Atmospheric Pressure

71. Lift Pump. — For over two thousand years, man has used the pressure of the atmosphere to help him raise water to a higher level. The device employed is the "suction" or

lift pump familiar to us at the country well. A simple experiment shows the principle upon which the lift pump is based.

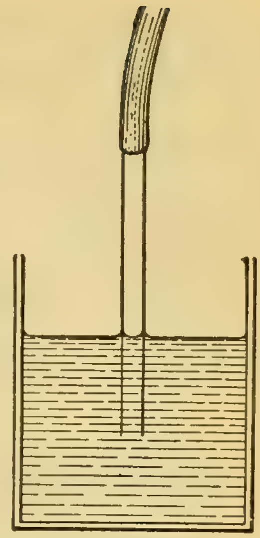


FIGURE 106.

EXPERIMENT 28. — Place in a jar of water the lower end of a long glass tube which has a short rubber tube on its upper end (Figure 106). *Why does the water stand at the same level in the tube as in the jar?*

Suck out through the rubber tube most of the air in the glass tube. *What pressure causes the water to rise in the glass tube?* Pinch tightly the upper end of the rubber tube. *Why does not the water run back into the jar?* Release the rubber tube. *Why does the water in the tube above the level of the water in the jar run back? Why is it necessary to remove some of the air in a tube if we want water to be pushed up into it?*

A lift pump is simply a device by which air is removed in a tube and a column of water lifted up into the tube by atmospheric pressure. Since this pressure holds up a column of water only 34 feet high, a lift pump, even if mechanically perfect, can only raise water if the piston valve is at no time more than 34 feet above the level in the well.

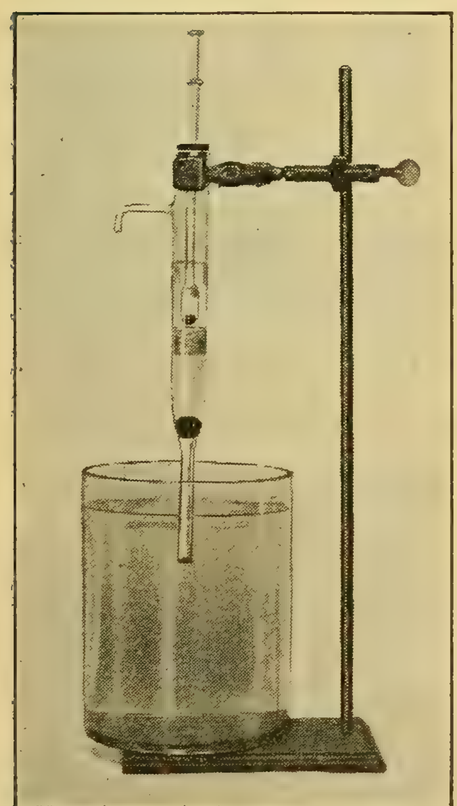


FIGURE 107. — GLASS LIFT PUMP.

EXPERIMENT 29. — Examine a glass model of a lift pump (Figure 107), noting the suction tube, the piston, the two valves, and the spout. Starting without any water in the pump, immerse the suction tube in a jar of water. Then operate the pump until it is in full action, noting the action of the *inclosed* air, the water, and the two valves on each successive stroke. *What is the main thing accomplished by the first few strokes of the pump?*

A cross section of a lift pump is shown in Figure 108. There are two valves, opening upward like trap doors; the inlet valve at the top of the suction pipe, and the outlet valve in the piston. When the piston moves upward, the outlet valve closes. The air pressure in the barrel is lessened. Then pressure of the air in the suction tube can open the inlet valve and admit air into the barrel from the suction tube.

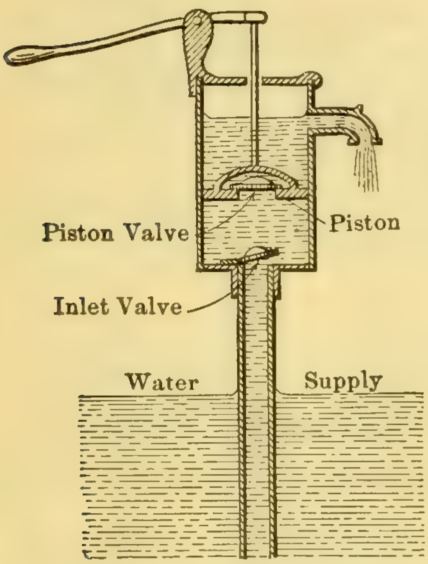


FIGURE 108.—LIFT PUMP, SECTIONAL VIEW.

On the down stroke of the piston, the pressure of the air in the barrel closes the inlet valve and opens the outlet valve in the piston, so that air can pass through. This air above the piston is lifted out of the pump on the next up stroke, the outlet valve closing. At the same time more air passes into the barrel from the suction tube. Thus the first half dozen strokes of the piston take the air out of the suction tube and lift it out of the pump. Meanwhile, the atmospheric pressure has been gradually pushing the water up into the suction tube as the air was removed. When the water is finally forced up into the barrel, the up stroke of the piston lifts it out of the pump just as the air was lifted out. Sometimes water is poured into the top of a pump to help start it. This makes the piston and the valves tighter in their operation. The piston of a pump should never be much over 30 feet above the water in the well.

72. Force Pump. — A force pump is used when water is to be delivered in a stream that is either continuous, or under pressure, or both. Its operation can be studied from a glass model.

EXPERIMENT 30. — Examine the glass model of a force pump, noting its parts (Figure 109). *How does the location of the outlet valve differ from that of a lift pump?* Try the action of the force pump. *Why is a force pump better adapted to produce greater pressure than a lift pump?*

Unlike a lift pump, the force pump does not have a valve in its piston. Another difference is that the outlet valve is

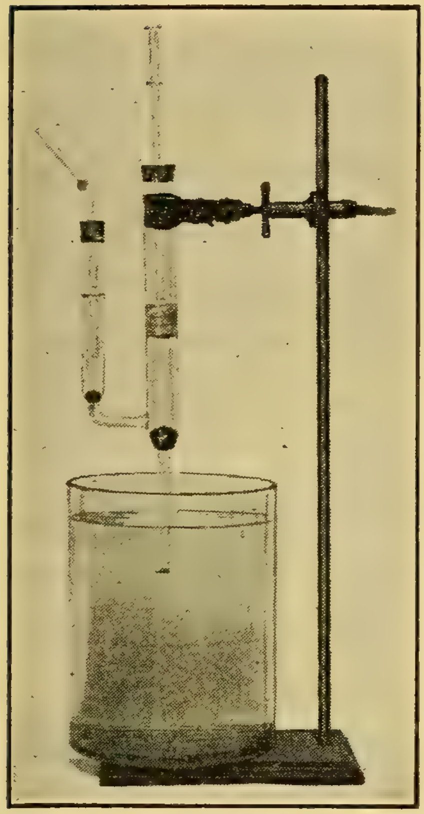


FIGURE 109. — GLASS FORCE PUMP.

The air dome is at the left.

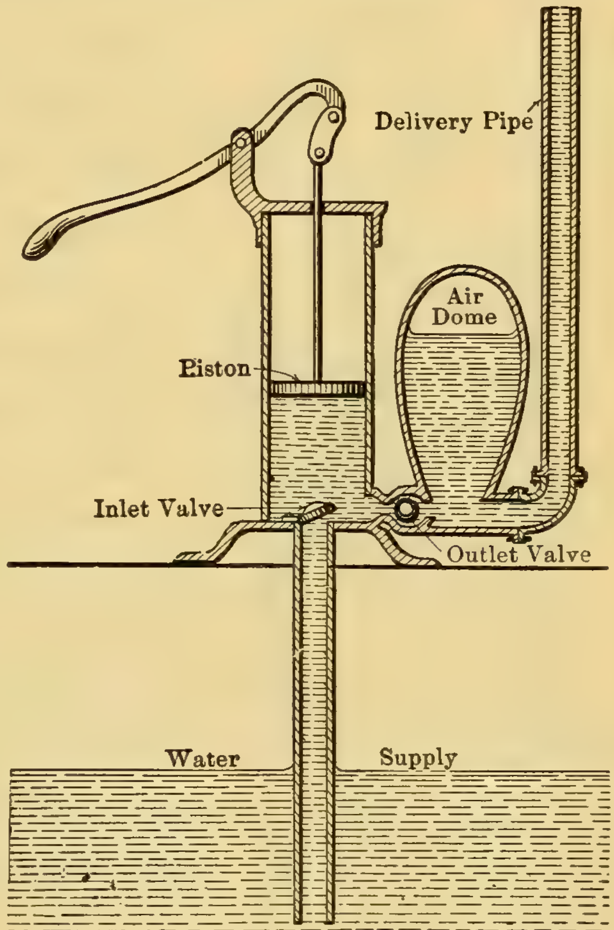


FIGURE 110. — FORCE PUMP.

The air dome gives steadiness to the flow, but does not add to the pressure.

nearly at the same level as the inlet valve. Often an air-chamber is attached to the side delivery pipe (Figure 110). The air in this chamber or dome is compressed on the down stroke of the piston, while on the up stroke the compressed air expands again, pushing water out of the delivery pipe. In this way the air cushion in the dome maintains a steadier flow of water.

The height to which water can be delivered by a force pump depends upon the pressure that can be exerted by the piston. This in turn is limited by the mechanical strength of the pump and its parts. While the lift pump is convenient for the water supply in rural sections and for occasional use in some factories, the force pump finds many more practical uses.

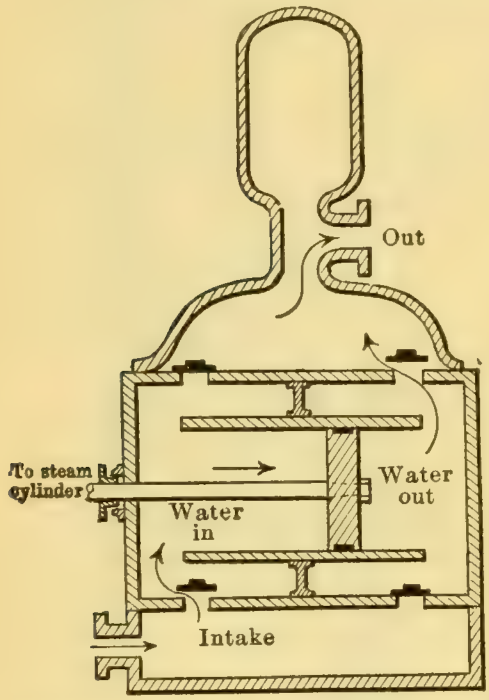


FIGURE 111.—WATER END OF STEAM PUMP.

The steam cylinder would be in a direct line at the left, with its piston on the same rod as the water piston.

73. Steam Pump. — A steam pump has two cylinders, one for water and one for steam (Figure 111). Each cylinder has a tightly fitting piston. These two pistons are connected by a piston rod. In the steam cylinder a set of valves admits the steam first on one side of the piston and then on the other. This alternating pressure of steam moves both pistons back and forth. When the water piston moves to the right, it leaves a partial vacuum behind it and water can enter through the inlet valve from a supply pipe. When the piston starts on its return stroke, the inlet valve closes and the piston forces the water in the cylinder through the outlet valve into the discharge pipe. The air cushion in the air chamber takes up any excess water pressure when the pump is discharging, thus preventing shocks to the pump and pipes. It also keeps up the pressure of the discharging water when the pump slows down near the end of one stroke and the beginning of the next. In this pump, while water is being admitted on one side of the piston, it

is being discharged on the other side, which doubles the capacity of the pump.

The pump just described is a single cylinder pump. Sometimes two pumps are placed side by side. In such a *duplex pump*, the steam valve of one pump is controlled by the piston rod of the other.

74. The Siphon. — The siphon is a bent tube of rubber, glass, or metal, used to carry a liquid over a small elevation to a lower level. It is convenient for emptying the liquid from a container that does not have a vent at the bottom and which cannot be tipped.

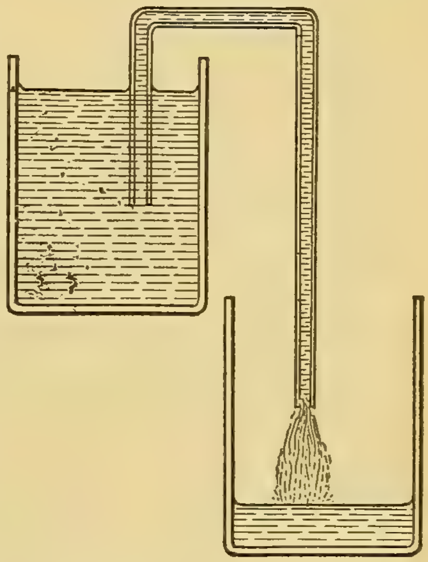


FIGURE 112. — SIPHON IN ACTION.

Atmospheric pressure keeps the short arm full; the excess weight of liquid in the long arm keeps it flowing.

EXPERIMENT 31. — Fill a glass siphon with water, and, keeping the lower end of the longer arm closed with the thumb, place the other arm in the water of a battery jar. Remove the thumb. (Figure 112.) *What happens? When does the water stop flowing?*

Replace the glass siphon with a rubber tube filled with water, and place one end of the tube in a battery jar of water. Raise the tube until the outer end is at the same level as the water in the jar. Remove the thumb.

Does the water flow? What pressure is pressing downward on the water in the jar? In what direction is this pressure being exerted in the rubber tube? Explain. What pressure pushes against the water in the open end of the tube? Why did not the water flow when the two arms were of equal length? Make the siphon arm outside the jar longer than the other one. *What happens? Which arm contains the greater weight of water?* This difference in the weight of water in the two arms causes the water to flow.

Lift the shorter arm of the siphon from the water in the jar. *In which direction does the siphon empty itself?*

The glass siphon must be filled with water before being inverted into the jar. If the siphon is left undisturbed, the water will run out the longer arm until the level in the jar reaches the lower end of the short arm of the siphon.

In each arm two forces are acting in opposite directions — the weight of the liquid and the atmospheric pressure. Since the atmospheric pressure transmitted to the short arm by the water in the jar equals that directly up against the long arm, the two pressures counterbalance each other. The water therefore moves in the direction of the greater liquid force, that is, out through the long arm. The atmospheric pressure keeps the short arm full, provided the length of this arm is less than 34 feet.

If the lower end of the short arm is raised from the liquid, the siphon will empty. If the liquid rises in the long arm until it is at the same level as in the vessel being emptied, the siphon will stop working, but it will not empty. Pouring more liquid into the discharging vessel starts the siphon working again. If the liquid is water, the bend of the siphon cannot be more than 34 feet above the water level around the short arm. With any other liquid, the greatest workable length of the short arm is the length of the column of that liquid which the atmospheric pressure will sustain. With this limitation in the height over which a liquid can be siphoned, a siphon can be used in any case where it is inconvenient to pour a liquid or to let it run out at the bottom of its container.

Glass siphons are much used in the filling of the reagent bottles in chemical laboratories and in drawing from the stock solutions in drug stores. They are most convenient in drawing off a liquid so as not to disturb the sediment at the bottom of a barrel or vat.

QUESTIONS

1. What accounts for the entrance of water into the lift pump? What limits the distance between the water level and the piston valve?

2. Make a labeled diagram of the lift pump showing the "suction tube," the barrel, and the two valves.

3. What is the main effect of the first half dozen strokes of the piston? What effect does the atmospheric pressure have?

4. State the action of each valve (*a*) on the up stroke of the piston; (*b*) on the down stroke, after water had filled the barrel to the spout.

5. Why is a little water sometimes poured into the top of the pump to start it?

6. What kind of stream is a force pump used to produce?

7. Make a labeled diagram of a force pump. How do its valves differ in location from those of a lift pump?

8. Make two diagrams showing the action of a force pump, one for the up stroke, the other for the down stroke. Show water levels and use arrows to indicate the direction of the water flow.

9. Explain the action of the air dome attached to a force pump.

10. What limits the height to which water can be delivered by a force pump?

11. Describe the construction and explain the operation of a steam pump.

12. What has to be done to start a siphon?

13. How do the air pressures at the two ends of a siphon compare? How do the water pressures compare?

14. What causes the liquid to flow through a siphon? What keeps the short arm filled?

15. Name two conditions under which a siphon will cease to operate.

16. State three practical uses of the siphon.

SUMMARY

Air has weight; 1 liter of air weighs 1.29 g at 0° C and 760 mm pressure; 12 ft^3 weigh a pound.

The atmosphere **exerts pressure** on all surfaces that it touches. Atmospheric pressure is exerted equally in all directions. It

will hold up a column of water about 34 feet high or a column of mercury 30 inches high.

A **mercury barometer** is essentially a straight glass tube, closed at one end, filled with mercury and placed upright with its open end beneath the surface of mercury in a reservoir. The empty space in the tube above the mercury is known as the Torricellian vacuum.

The **aneroid barometer** is a metallic box from which the air has been partially exhausted, having a thin, slightly curved cover. Very slight changes in the atmospheric pressure alter the curvature of the cover and such changes are registered on the scale of the instrument.

Normal atmospheric pressure at sea level is 76 cm or 30 in of mercury. Steam engineers use 14.7 lbs/in^2 as their normal.

Atmospheric pressure decreases with the altitude, about 0.1 inch for every 90 feet of ascent. This gives a means of measuring altitude with a barometer.

The atmosphere extends at least 100 miles above the earth, but at half that height the air is extremely thin.

A **lift pump** is a device by which air is removed from a tube and a column of water lifted up into the tube by atmospheric pressure.

The solid piston of a **force pump** pushes water out through a valve near the bottom of the cylinder, thus compressing a cushion of air in the air chamber. This air then expands, pushing water out of the delivery pipe. The height to which water can be delivered by a force pump depends upon the pressure exerted on the piston and the mechanical strength of the pump parts.

A **steam pump** has two cylinders, one for water and one for steam, with a tightly fitting piston in each. Steam moves the pistons so that water is pumped.

A **siphon** is a bent tube used to carry a liquid over a small elevation (not more than 34 feet for water) to a lower level. Its

operation depends upon the difference in the effective pressures in the two arms.

Siphons are used for emptying containers that cannot be tipped, or emptied from the bottom.

EXERCISES

1. The glass of an incandescent electric light bulb can be pierced with a tiny gas flame. With this and a balance for weighing, how would you prove that air has weight?

2. How many pounds of air are there in a classroom $30 \times 20 \times 12$ feet?

3. Why are we not crushed by the atmospheric pressure on our bodies?

4. What is the scientific explanation of the old saying, "Nature abhors a vacuum"?

5. Explain the process of taking air into the lungs.

6. Why is the cap at the top of a can of oil loosened before pouring the oil out of the spout?

7. How does a fountain-pen filler work?

8. Campers punch two holes in the cover of a can of condensed milk. What is the purpose of each hole?

9. Describe and explain what happens when a large narrow-mouth bottle full of water is inverted.

10. Explain the method of collecting gases over water used in the chemical laboratory.

11. How deep a lake of water would exert the same pressure on the land as the air ordinarily does?

12. Describe the experiment with the Magdeburg hemispheres. What was shown by it?

13. What will be the length of the water column held up by the air pressure when the barometer reads 29 inches?

14. Why does the Fortin cistern barometer have a movable bottom?

15. Compare the aneroid with the mercury barometer as to convenience, sensitiveness, and accuracy.

16. During a certain year, the barometer readings at New York varied between 28.5 and 31 inches. What is the difference in lbs/in^2 pressure between these readings?

17. On a clear dry day, a person starting from sea level, where the barometer reads 30 inches, finds that the mercury drops 1.5 inches as he ascends a mountain. How high did he climb?

18. Why are airplanes equipped with aneroid barometers?

19. What enables one to drink soda water through a straw?

FIGURE 113.

20. Why must air be sucked out of the top of a pipette (Figure 113) in order to fill it with a liquid? When the top is tightly closed with a finger tip and the pipette lifted out of the jar, the liquid does not run out. Explain.

21. Why must a pump for a deep well differ from that used for a shallow well?

22. Why do fire engines have a large air dome attached to the pump?

23. What kind of pump is generally used (*a*) in a farmhouse kitchen; (*b*) to fill the tank on the roof of an apartment house; (*c*) to rid the hold of a sailing vessel of water, and (*d*) to take the water from a sewer excavation in a street?

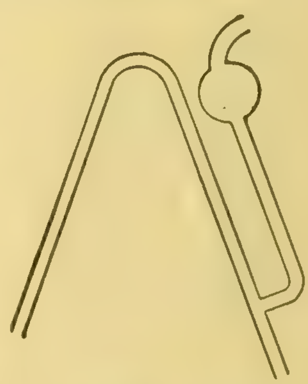


FIGURE 114.

24. Explain how the aspirating siphon shown in Figure 114 is started. Why is such a siphon used with corrosive liquids?

25. Why can only one arm of a siphon be longer than 34 feet?

26. How can the rate of flow in a siphon be increased?

27. The bend of a siphon is 3 feet above the water level in a tank and the lower end of the long arm is 6 feet below that water level. Make a labeled diagram of the siphon indicating (*a*) the net upward pressure of the water in the short arm; and (*b*) the net downward pressure of the long arm. What is the effective pressure that makes the siphon flow?

28. State three widely different reasons for using siphons.

29. Why does the captain of a leaking ship have the pumps manned instead of siphoning the water out of the hold?

CHAPTER VIII

BOYLE'S LAW AND COMPRESSED AIR

75. Boyle's Experiment. — A bicycle pump enables one to take air and squeeze it into a smaller space within the tire. Repeated strokes of the pump result in a large volume of the outer air being compressed within the smaller space of the tire. If the pump is disconnected and the inlet valve of the tire opened, air rushes out with great force, showing that it has much greater pressure than the outside air. Making the outer air, then, occupy a smaller volume gave it a greater pressure. Compressed oxygen from a tank will expand to many times its own volume at atmospheric pressure. Here the volume of the gas has been greatly increased at the expense of a decrease in pressure.

FIGURE 115.

The relation between the pressure and volume of gases was first defined in 1662 by Robert Boyle, an Irishman. We may repeat his experiment with a J-shaped tube.

EXPERIMENT 32. — Add mercury to the open end of a glass J-tube until the mercury stands at the same level in the two arms. Measure the length of the column of air confined in the closed arm. This volume of air is at atmospheric pressure. *Why?* Read a barometer for the atmospheric pressure.

Pour mercury into the open arm till a column is obtained whose length above the level in the closed arm is equal to that of the barometric column (Figure 115). *What pressure is now being exerted upon the confined air? What change has taken place in the length*

of the air column? Pour mercury out of the tube until the difference in levels is equivalent to half the barometric pressure. *What volume does the air now have? What is the total pressure on the inclosed air?*

State the relation between the volume of a gas and the pressure exerted on it, when the temperature remains constant.

FIGURE 116.— The air expands as the tube is drawn out of the mercury.

Like Boyle, we find by the preceding experiment that doubling the pressure on the air makes the volume half as much as before. With three times the pressure, the volume would be one third as great. For pressures less than one atmosphere, Boyle used a straight glass tube closed at one end and partly filled with mercury. He thrust the open end into a reservoir of mercury, and found that a *decrease* in pressure resulted in a corresponding *increase* in volume (Figure 116). Then he was able to state the law that now bears his name.

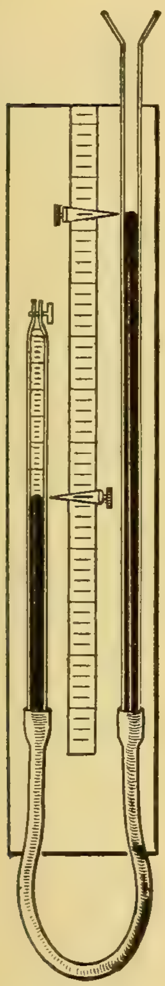


FIGURE 117.— Volumes are measured directly in the graduated tube; pressures, as in the J-tube.

76. Boyle's Law.— *The volume of an inclosed mass of gas at constant temperature varies inversely with the pressure exerted on it.*

Figure 117 shows a Boyle's Law tube convenient for pressures either greater or less than the atmospheric. The following table gives a set of readings with the instrument, as well as a third column for the product of the pressure (P) by the volume (V).

Observations (at 20° C)	Pressure (P) (cm. of Mercury)	Volume (V)	Product $P \times V$
1	75.0	35.7	2677
2	86.8	30.7	2673
3	108.7	24.6	2674
4	71.7	37.3	2674
5	68.0	39.3	2672

The products are almost equal and would be exactly equal were it possible to get more exact readings with the instrument. Then:

$$PV = \text{a constant}$$

Let P and V stand for one pair of values and P' and V' for another pair, then:

$$PV = P'V'$$

Forming a proportion from the two equal products:

$$\frac{V}{V'} = \frac{P'}{P}$$

This is another way of stating Boyle's Law and is convenient for solving problems involving the law.

Problem. A gas has a volume of 48 cm^3 at 750 mm pressure. What will be its volume at the same temperature when the pressure is increased to 800 mm?

P is 750 mm; P', 800 mm; V, 48 cm^3; and V' is to be found. Substituting these values in the proportion:

$$\frac{V}{V'} = \frac{P'}{P} \qquad \frac{48\ cm^3}{V'} = \frac{800}{750}$$

Clearing of fractions:

$$800\ V' = 750 \times 48\ cm^3$$

Whence:

$$V' = \frac{750}{800} \times 48\ cm^3 = 45\ cm^3,$$ the volume of the gas at 800 mm. *Answer.*

Problem. A tank contains compressed oxygen at 144 lbs/in^2 pressure. How many ft^3 of the compressed gas are in the tank, if 50 ft^3 of oxygen at 15 lbs/in^2 pressure, at the same temperature, can be taken from it?

P is 144 lbs/in^2; P', 15 lbs/in^2; V is to be found; and V' is 50 ft^3. Substituting these values in the proportion:

$$\frac{V}{50 \text{ ft}^3} = \frac{15}{144}$$

$$V = \frac{15}{144} \times 50 \text{ ft}^3 = 5.2 \text{ ft}^3. \quad \textit{Answer.}$$

PROBLEMS

(*Assume constant temperature in these problems.*)

1. The compressed air used in operating an airbrake is under a pressure of 75 lbs/in^2. To what volume will a cubic foot of it change when it escapes to the outer air where the pressure is 15 lbs/in^2? Explain.

2. What will be the volume of 60 ft^3 of a gas when its pressure changes from 762 mm to 750 mm?

3. How many ft^3 of oxygen can be obtained from a tank containing 2 ft^3 of the gas under 100 lbs/in^2 pressure, when the oxygen is collected under 15 lbs/in^2 pressure?

4. 120 ft^3 of a gas at 75 cm pressure is compressed so that it occupies 100 ft^3. At what pressure is it then?

5. There are 90 ft^3 of steam under a pressure of 220 lbs/in^2 in a boiler. What volume will the steam occupy at a normal atmospheric pressure of 15 lbs/in^2?

6. How many cubic feet of air at normal atmospheric pressure must be pumped into a tire having a volume of 0.75 ft^3, in order to inflate it to a pressure of 80 lbs/in^2?

77. Explanation and Limitations of Boyle's Law. — The pressure of a gas in a container is not due to the weight of the gas, but to the fact that its molecules strike the walls of the containing vessel with the speed of a rifle bullet. A rapid stream of bullets from a machine gun will batter down an obstruction of considerable strength. In the automobile tire, millions of molecules are constantly striking every square inch of the wall of the inner tube (Figure 118), and have the same effect as that of a force of many pounds constantly applied. When we pump in more air, more molecules are crowded into the tire and the inner wall is bombarded with still greater force. In this way, the decrease in the volume of the air results in a correspondingly greater pressure. When we increase the volume of a gas at constant temperature, there is a smaller number of molecules in a given space to bombard the inclosing walls and the pressure decreases.

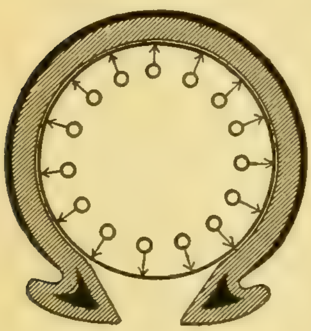


FIGURE 118. — The circles represent molecules bombarding the tube.

Boyle's Law is true for most gases at ordinary temperatures and pressures. It has been found, however, that certain deviations exist, particularly for gases under great pressures. The law fails to take into account the attractions and repulsions that exist between the molecules of gases under certain conditions. Several mathematical corrections for such factors have been worked out so as to give a modified expression of the law that holds true universally. The deviations of gases from Boyle's Law are, under ordinary circumstances, so slight that they may be disregarded. The law is a most useful one in physics and chemistry, and finds many applications in engineering as well.

78. The Air Pump. — A simple type of air pump consists of a piston fitting tightly into a cylinder with two valves at the bottom.

EXPERIMENT 33. — Connect an air pump with a bell jar provided with a pressure gage. Locate the two valves of the pump. Make an up stroke of the piston. *Which valve opens? What becomes of the air that is pumped out of the jar?* Make the down stroke of the piston. *Which valve closes? Which valve opens? What becomes of the air in the cylinder?* Make several up and down strokes of the piston. *What does the reading of the pressure gage indicate?* Continue pumping as long as there is a decrease of pressure in the jar. *What partial vacuum can be obtained with the pump?*

Place under the jar a tumbler with a sheet of rubber stretched across its top. Exhaust some of the air from the jar (Figure 119). *What happens to the rubber diaphragm? Explain.*

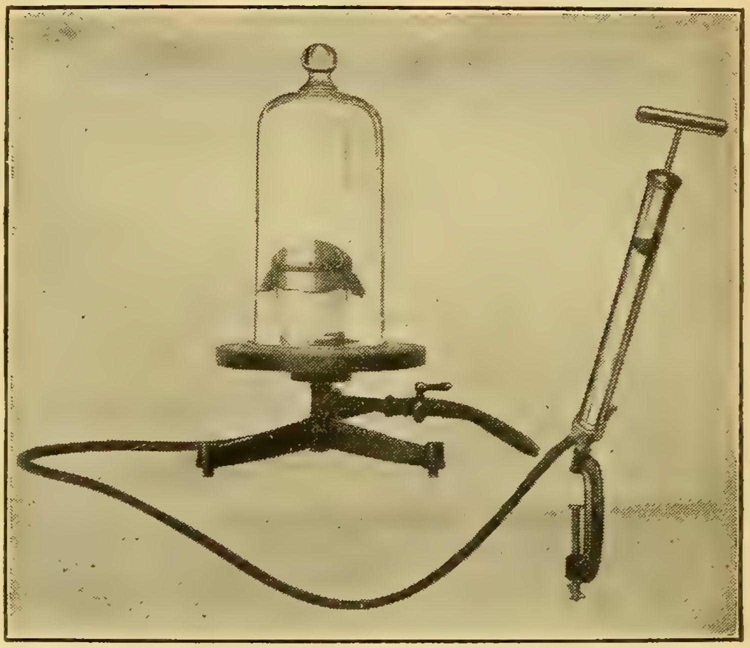


FIGURE 119. — Part of the air in the bell jar has been pumped out.

On the up stroke of the piston of a simple air pump (Figure 120), the air pressure in the cylinder is reduced, and the greater pressure of the air in the bell jar opens the inlet valve in A, and the air expands into the vacant space left by the piston as it rises in the cylinder. On the down stroke of the piston, the pressure of the air in the pump cylinder closes the valve in A and opens the outlet valve in B, through which the air escapes. On the next stroke the valve in B closes, while the valve in A opens and more air is ex-

hausted from the jar. A pressure gage shows a gradual decrease of pressure in the bell jar with the successive strokes of the pump. Finally, the pressure of the air remaining in the jar becomes too weak to open the valve, A. For this reason a high degree of vacuum cannot be attained with a simple air pump. In many pumps the valves are mechanically opened and closed. Another of the defects of the simple pump is that the bottom of the piston cannot be made to fit the bottom of the cylinder with perfect accuracy, thus making it impossible to expel all the air in the cylinder on the down stroke.

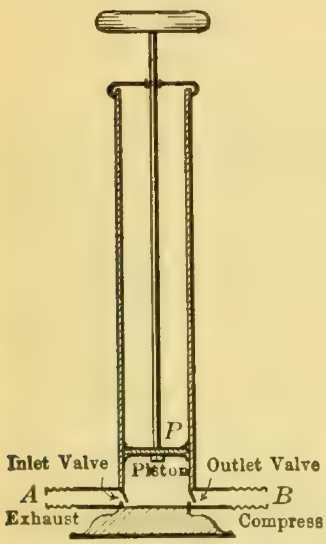


FIGURE 120.—SIMPLE AIR PUMP.

Air will be exhausted from any receptacle connected to A, or compressed into one connected to B. Both valves cannot be open at the same time, but they are thus pictured to show how they swing.

In the Geryk pump this disadvantage is overcome by an oil seal at the bottom of the cylinder. There is another oil seal above the piston to prevent air leakage at the piston valve. An efficient Geryk pump will produce a vacuum of $\frac{1}{5000}$ mm. Higher vacuums are obtained with glass pumps in which mercury plays the part of the piston. Toepler's air pump is of this type. Langmuir invented a modified form of the mercury pump which gives a vacuum of less than 0.000001 mm.

Household vacuum cleaners operate by means of a vacuum pump of the mechanical type or by means of a small rotary fan that acts on the same principle. The dust from the fabric is sucked into the exhaust pipe and then passes into the receptacle designed to receive it. With electrical power, household vacuum cleaners are efficient, but those operated by hand are not effective and entail too much labor in their use.

QUESTIONS

1. (*a*) Make a labeled sectional drawing of an air pump connected to a bell jar. (*b*) How is the volume and pressure of the air below the piston affected by its down stroke?

2. What change takes place in the volume of the oxygen as it escapes through the valve of a commercial tank of the gas?

3. Make three sectional drawings of the J-tube apparatus, showing how increased pressure affects the volume of the air inclosed in the short arm.

4. State Boyle's Law in words and in the form of an equation.

5. If the product PV equals a constant, state how changing the value of P affects the value of V.

6. Explain Boyle's Law in terms of bombardments of molecules, when volume of inclosed air is (*a*) increased; (*b*) decreased.

7. For what range of pressures does Boyle's Law hold true? What deviations exist and what causes them?

8. Make a simple diagram of an air pump connected to a bell jar, showing the two valves.

9. Letter the valves on the diagram of Question 8. What happens to the two valves, the air in the bell jar, and to the air in the pump cylinder on (*a*) the up stroke of the piston; and (*b*) the down stroke of the piston?

10. Why can a higher degree of vacuum be obtained with a Geryk pump than with a simple air pump?

11. Explain the operation of a household vacuum cleaner.

Compressed Air

Compressed air is a most useful means for power transmission over both short and long distances. It has the advantage of always being ready to work at full capacity and has a low maintenance cost. For these reasons, compressed air finds a wide variety of practical applications.

79. Air Compressors. — The *bicycle pump* (Figure 121) is the simplest type of air compressor. It consists of a cylinder and piston with a concave leather disk on its under side. On

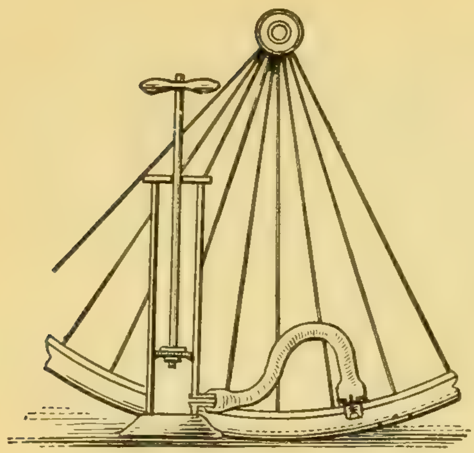


FIGURE 121.

Air can leak by the flexible edges of the piston on the up stroke, making the piston an intake valve.

the up stroke of the piston, air leaks in around the loosely fitting leather disk so as to fill the cylinder. On the down stroke, the concave disk fits tightly against the sides of the cylinder and compresses the entrapped air until its pressure becomes greater than that of the air in the tire. Then the inlet valve in the tire opens and air is forced in. The simple air pump, described in § 78, may also be used as a compression pump, by leaving the intake open to the atmosphere, and connecting the discharge to a tire or a compression tank.

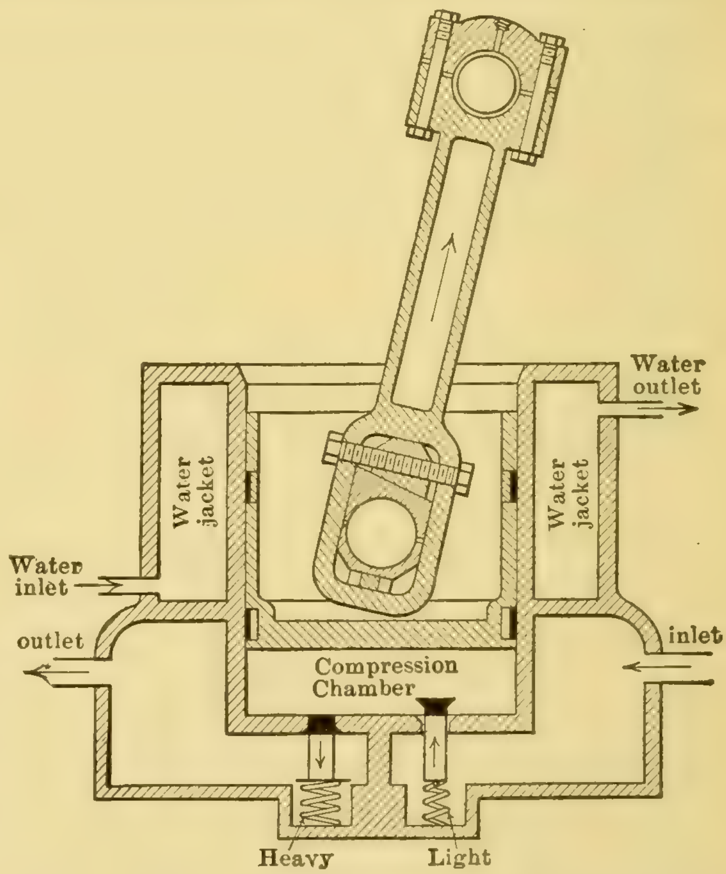


FIGURE 122. — SECTION OF ONE CYLINDER OF AIR COMPRESSOR.

Water is kept flowing through the water jacket to carry away the heat produced during the compression of the air.

Large *air compressors* (Figure 122) are operated by steam or electricity and usually have a tank that acts as a reservoir. Often an automatic switch is provided, that starts the machine pumping when the air pressure in the reservoir drops to a certain point, and stops the machine when a cer-

tain maximum pressure is reached. Since air compressors require an air supply, they can be operated as exhaust or vacuum pumps. Vacuum-cleaning systems in hotel and office buildings have a series of pipes connected with a vacuum pump in the basement.

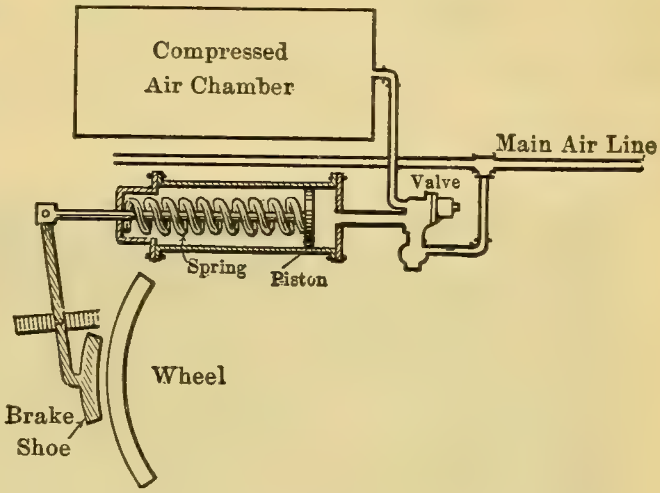


FIGURE 123.—SECTION OF AIR BRAKE.

The triple valve can (*a*) admit air to the chamber; (*b*) allow air from the chamber to act against the brake piston; (*c*) release the air from the brake cylinder to the atmosphere.

80. Air Brakes give the widest use to compressed air. In the diagram of the air brake (Figure 123), the compressed air chamber, which is under the car, is connected with the brake cylinder by a pipe, and with the main reservoir on the locomotive by the main air line. An air compressor on the locomotive maintains an air pressure of 75 lbs/in^2 in the main and auxiliary reservoirs and the pipes connecting them. The brake cylinder, however, is cut off by the triple valve. When the pressure drops below 75 lbs in this connected system, the valve shuts off the connection with the main reservoir on the engine and air is admitted to the brake cylinder from the compressed air chamber. The compressed air moves the piston which applies the

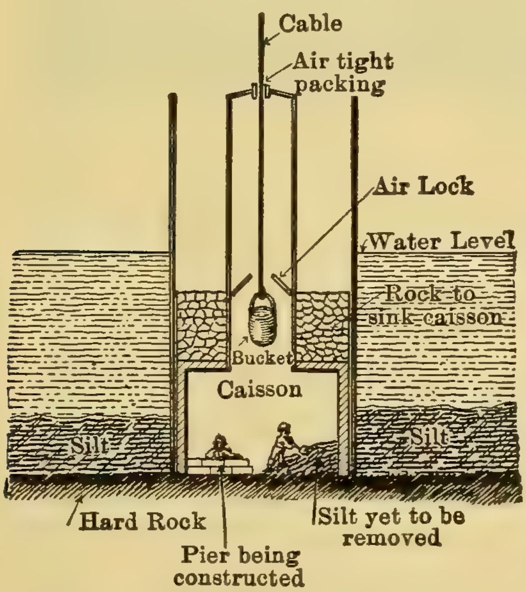


FIGURE 124.—CAISSON IN PLACE.

Air pressure prevents water from entering at the bottom.

brake shoes to the car wheels. The brakes are released by the air pressure from the main reservoir, cutting off the air supply from the brake cylinder. Then the spring pushes back the piston, which takes the shoes from the wheels. In the application of the brakes, the engineer moves a lever in

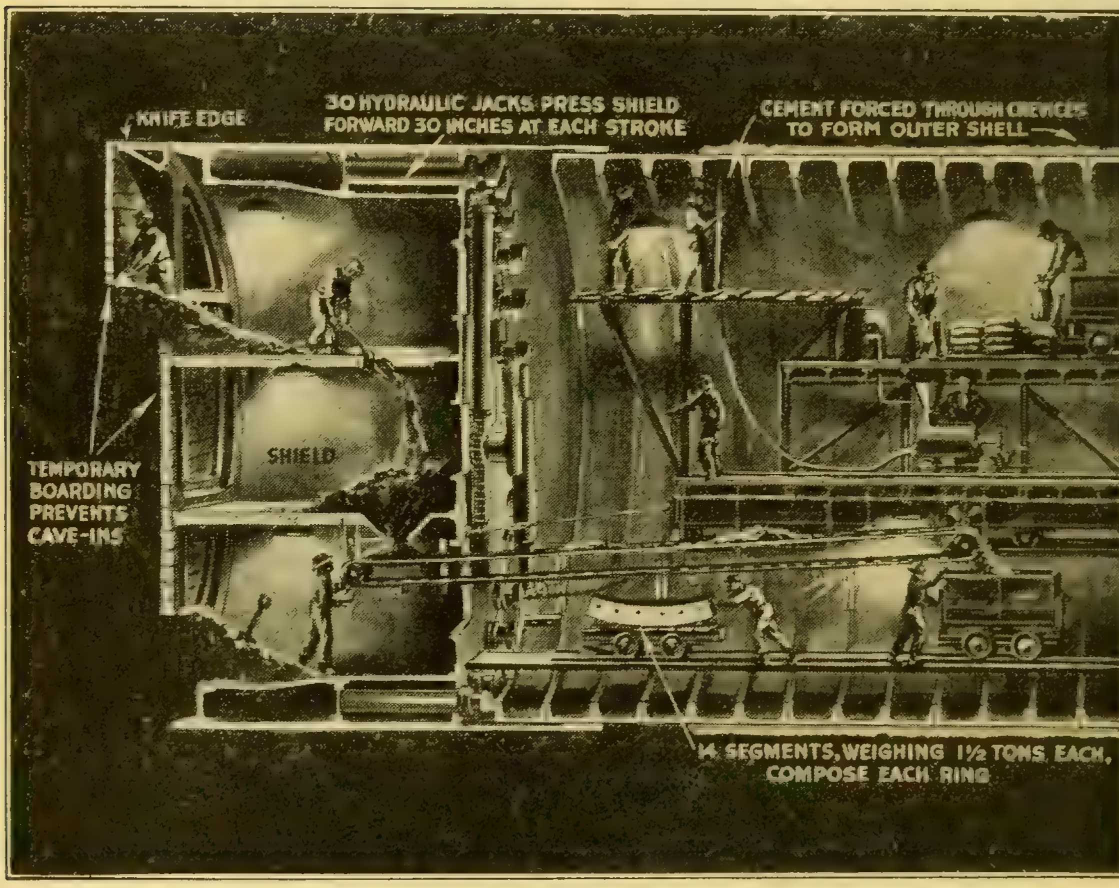


FIGURE 125. — DRIVING A TUNNEL

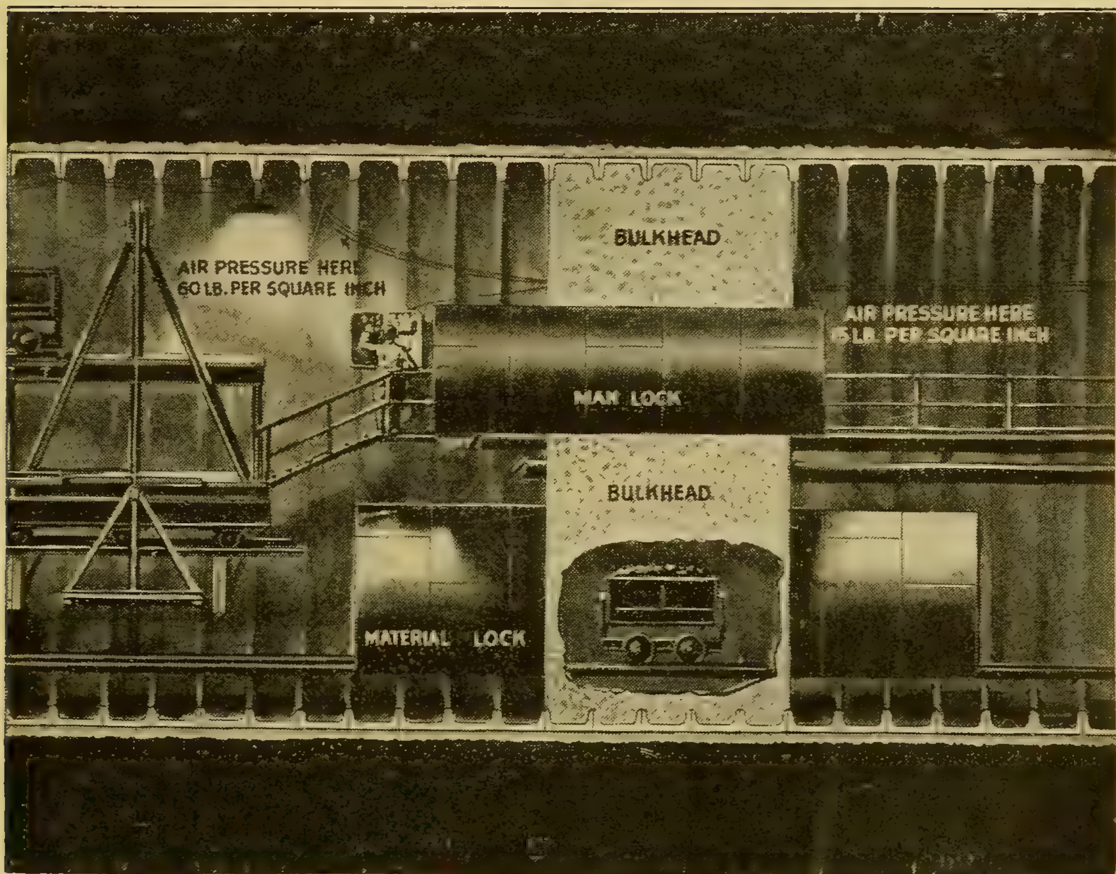
The shield, at the extreme left, is forced forward by the hydraulic jacks, behind the shield. Air pressure prevents

the cab to reduce the controlling air pressure. The same effect occurs when the air-hose couplings part when a train breaks in two.

Trolley cars have a small air compressor electrically operated and with a reservoir kept filled by the regulating action of an automatic switch. The brakes are applied by the motorman moving a control lever with his hand. The

switches controlling the speed of the car are often operated by a compressed-air system.

81. Caissons and Other Applications. — The *caisson* (Figure 124) is essentially a box open at the bottom and weighted so that it will sink in the mud of a river or harbor in which an

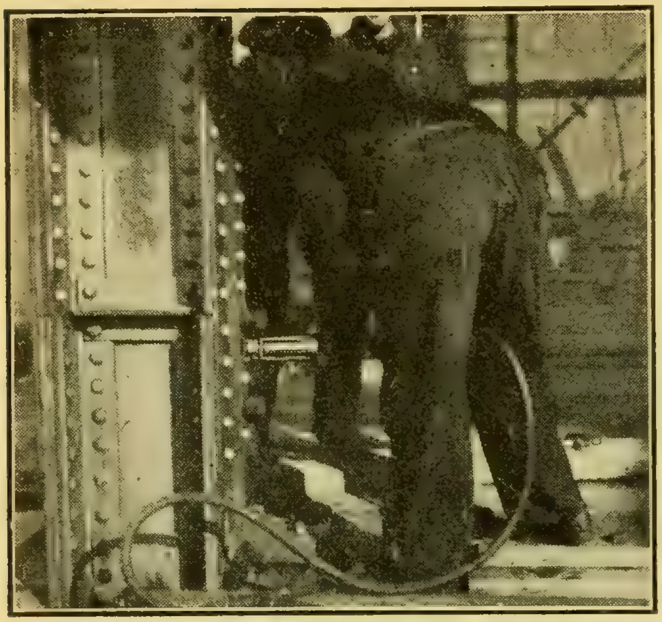


Courtesy Popular Science Monthly.

UNDER A RIVER BED.

as the work proceeds. The construction of the tunnel is shown going on the water from entering the open shield.

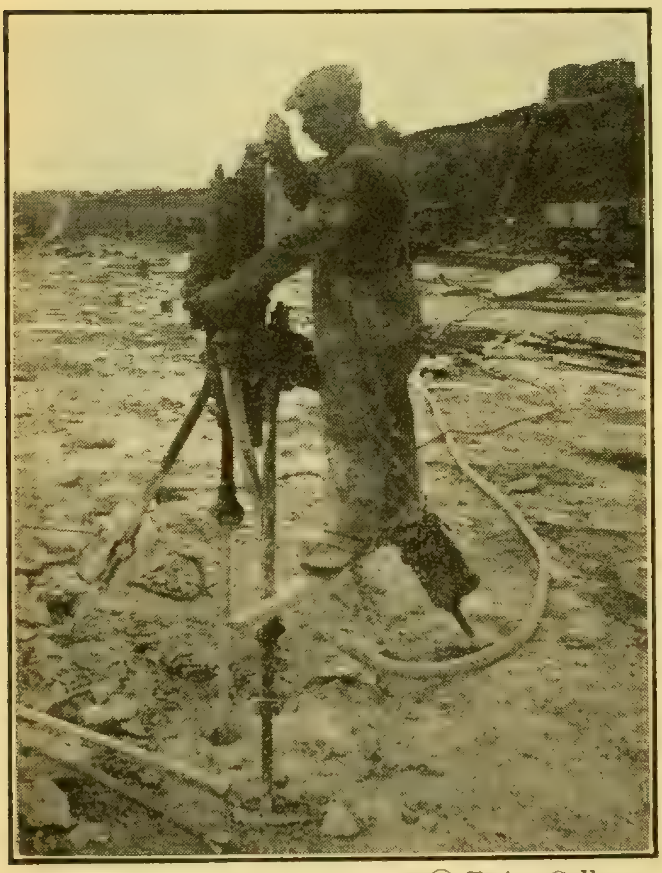
excavation is to be made. Compressed air is used to maintain a pressure sufficient to prevent water from entering the caisson. Workmen and material pass in and out through air locks. When enough material is excavated from the bottom to give the desired foundation, masonry is built within the caisson for the pier or building foundation. Sometimes the caisson forms a part of the permanent structure.



Courtesy American Bridge Co.

FIGURE 126. — PNEUMATIC RIVETER.

This is being held against the end of a hot rivet. Its blows form a head on the rivet.



© *Ewing Galloway.*

FIGURE 127. — DRILLING ROCK WITH COMPRESSED AIR.

Another form of the caisson is the *pneumatic shield* (Figure 125) used in constructing tunnels through material too soft to admit of boring. The walls of the subway or railway tube are built within the shield which is gradually pushed ahead for the next section.

Pneumatic tools serve many purposes and their use is increasing. Among them are cutting and chipping tools for rock and metal; coal, rock, and metal drills; and pneumatic riveters (Figure 126). In the drill (Figure 127), compressed air admitted to the cylinder drives the plunger forward so that its motion is passed on to the drill tool itself (Figure 128). A single automatic valve mechanism admits air alternately to the plunger and permits the expanded air to escape.

In the *pneumatic cash*

carriers of department stores, small cylinders fit tightly into metal tubes. Rapid propulsion is obtained by admitting compressed air behind the carrier and exhausting the air in front of it.

Compressed air is used for the forced draft of forges and blast furnaces, for agitating and aërating liquids, for lift-

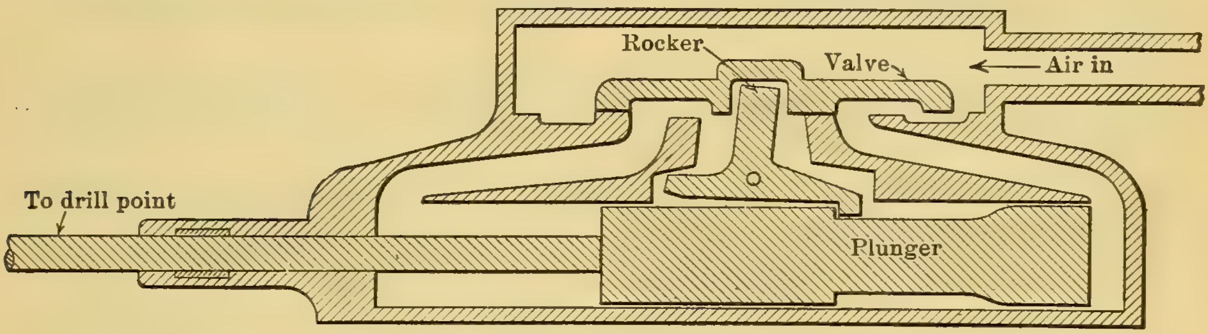


FIGURE 128. — SECTION OF HEAD OF COMPRESSED-AIR DRILL.

The air is about to drive the plunger forward. At the end of the stroke, the valve shifts and air admitted at the opposite end drives the plunger back. The space around the rocker is connected to the atmosphere, so that the expanded air can escape.

ing acids and other heavy liquids in manufacturing plants, for spraying paint, for sand blasts, and for numerous other purposes.

The zero point on steam gages and on all gages used with compressed air and other gases indicates atmospheric pressure (15 lbs/in^2). Thus a reading of 50 lbs on the gage means 50 lbs more than atmospheric pressure, or 65 lbs/in^2 *absolute pressure.*

QUESTIONS

1. What three advantages has compressed air as a means of power transmission?

2. Make a labeled diagram of a bicycle pump connected to a tire, showing the cylinder, the piston, and the valve. Indicate by arrows where air enters the cylinder and where it leaves.

3. Explain the automatic operation of a large air compressor.

4. What are the essential parts of a vacuum-cleaning system in a large office building?

5. What is the purpose of (*a*) the air compressor on a locomotive; (*b*) the auxiliary air reservoir under each car; and (*c*) the compressed air lever in the engineer's cab?

6. Explain how the air brakes are applied to the wheels of a railroad car. In what other way may this sometimes occur?

7. What is a caisson? For what and how is it used?

8. Describe the operation of a pneumatic shield in the building of a tunnel.

9. How are the pneumatic cash carriers of department stores operated?

10. Briefly describe three other industrial applications of compressed air that have not been referred to in the preceding questions.

SUMMARY

Boyle's Law states: The volume of an inclosed mass of gas at constant temperature varies inversely with the pressure exerted on it.

$$\frac{V}{V'} = \frac{P'}{P}$$

Problems based on Boyle's Law **are solved** by substituting values for the three quantities that are known in the equation just given, and then solving the equation for the fourth or unknown quantity. Constant temperature is assumed in many of these problems.

The pressure of a gas in a container is not due to the weight of the gas, but to the rapid bombardment of the inner walls by the molecules.

Decreasing the volume of a gas, without change of temperature, crowds more molecules into a given space, so that the more vigorous bombardment of the inner walls of the container results in a **greater pressure.**

Increasing the volume of a gas, without change of temperature, means fewer molecules in a given space, a lessened bombardment by the molecules, and a **decreased pressure.**

A simple air pump consists of a piston fitting tightly into a cylinder with two valves at the bottom.

Air pumps that give a higher degree of vacuum owe their greater efficiency to more accurate fitting of piston to cylinder and the use of an oil seal to prevent leakage at the valves. Still more efficient air pumps have glass parts with mercury acting as the piston.

Vacuum cleaners are either air pumps of the mechanical type or employ a rotary fan that acts upon the same principle.

Compressed air is a cheap means of transmitting power over short distances and is always ready to work at full capacity.

The bicycle pump, the simplest type of air compressor, consists of a cylinder and a piston with a flexible concave disk on its under side. The piston itself acts as one valve, the other usually being in the tire inlet.

Large air compressors operate by steam or electricity and usually have a tank or reservoir for storage.

Air compressors are operated as **vacuum pumps** in the vacuum-cleaning systems of large buildings.

Compressed air has numerous practical **uses** of great importance. Among them are the air brake; the caisson, so useful in building piers and foundations; the pneumatic shield, that enables tunnels to be built through muddy river beds; pneumatic tools in a wide variety of forms; cash carriers in department stores; and a long list of technical and industrial uses.

EXERCISES

1. What did Boyle mean by the "spring of the air"?

2. Why does air rush out of a football bladder when the inflating tube is opened? What relative space is occupied by the air formerly inclosed by the ball?

3. What gases are compressed and sold? Do the containing tanks for such gases need to be rigid or tenacious? Explain.

4. Explain why balloons are not fully inflated at the beginning of their flight.

5. A pressure gage reads 0 before being attached to an air tube used to inflate tires. What does this mean? What absolute pressure is indicated by a gage reading of 75 pounds?

6. Steam inside a boiler has an absolute pressure of 165 lbs/in^2. What would a pressure gage indicate if attached to a boiler outlet?

7. When steam is admitted to the cylinder of a steam engine against the piston, what does the steam try to do? What results from the action of the steam?

8. As steam pushes the piston of a steam engine, how does the steam pressure change? Why?

9. Explain why sudden and large changes in altitude are sometimes attended by serious bodily disturbances. Remember that the body contains dissolved air in all the blood vessels as well as in the lungs.

10. Workmen in tunnel operations work under pressure of as much as 3 atmospheres. What precautions must be taken by the workmen as they enter and leave the tunnel head? Why?

11. A tank of oxygen in the chemical laboratory contains 4 cubic feet of gas at 150 lbs/in^2 gage pressure. How many pint bottles (about 30 in^3) can be filled from it?

12. A bottle of air is pushed mouth downward into water until water half fills the bottle. What is the air pressure inside the bottle?

13. A partly inflated toy balloon under an air pump receiver expands to 3 times its original volume as air is withdrawn from around it. What is the pressure now (*a*) inside and (*b*) outside the balloon?

14. How many cubic inches of air at normal pressure are required to fill an inner tube of an automobile tire at 75 lbs/in^2 gage pressure, if the tire holds 800 in^3 when inflated?

15. Would it be to the advantage of the consumer or of the gas company if the state should require the gas company to furnish gas at a pressure of 6 inches of water instead of a 3-inch pressure? Explain. Would the difference be important or slight?

16. A tire contains 1000 in^3 and is under a gage pressure of 75 lbs/in^2. What space will this air occupy if a blowout occurs?

17. If 75 cm^3 of air under the atmospheric pressure of 15 lbs/in^2 be subjected to a total pressure of 45 lbs/in^2, what volume will it then have?

18. A basket ball having an internal volume of 500 in^3 is filled with air at an absolute pressure of 25 lbs/in^2. The ball is then opened and all the air pressed out. What volume does the pressed-out air take?

19. The volume of an oxygen gas cylinder for the calcium light is 2.5 ft^3. It contains oxygen under a total pressure of 12 atmospheres. What would be the volume of oxygen if measured at the ordinary pressure?

20. If an automobile tire has a capacity of one cubic foot and the tire is under a gage pressure of 75 lbs/in^2, what volume does the air occupy when the tire bursts?

CHAPTER IX

HEAT AND EXPANSION

All life, both plant and animal, depends upon receiving an adequate supply of heat. For this reason the production of heat was one of the first problems of the savage. From the earliest times man has been concerned with methods of securing heat for his shelter, for cooking his food, and for fashioning his implements of warfare and the chase. Civilization has advanced in a practical way as the means of controlling heat have been developed.

The sources of heat are numerous. The kettle is heated when it is put on a stove that is hotter than itself. An object may become warmer even though heat is not directly applied to it. Ice and snow on a mountain top are melted by the conversion of the energy of the sun's rays into heat. Other bodies change their thermal condition by converting other kinds of energy into heat.

Sources of Heat

82. Heat from Work. — The hand rubbed on a desk is warmed. Car axles and the bearings of machinery, if not properly oiled, may be heated until they are damaged. In each of these cases, work has been done in overcoming friction. That this work produces heat may be shown by a simple experiment.

Experiment 34. — Bore with a small drill into the end grain of a piece of hard wood. The drill becomes too hot to touch. *Why?* Now

bore into soft wood. *Is the drill as warm? Why? How does the amount of work done in boring affect the amount of heat produced?* We learn from these tests that heat is produced by working against *friction.*

Molecules of a solid resist any effort to displace them. If this resistance is overcome, heat is produced.

Experiment 35. — Lay a wire nail on an anvil and hammer it flat. It will be much warmer than before hammering.

Some of the work done in hammering has set the molecules of the iron into more rapid vibration. In this way heat has been produced by *percussion.*

Experiment 36. — Make some tinder by heating an old linen handkerchief in a closed tin can until the linen is entirely charred. Place a bit of this tinder in the concave end of a piston that, when oiled, fits closely into a stout glass or metal tube closed at the bottom (Figure 129). Drive the piston down into the tube with a quick, strong push. The tinder will be ignited and, when the piston is withdrawn, it may be blown into a bright glow.

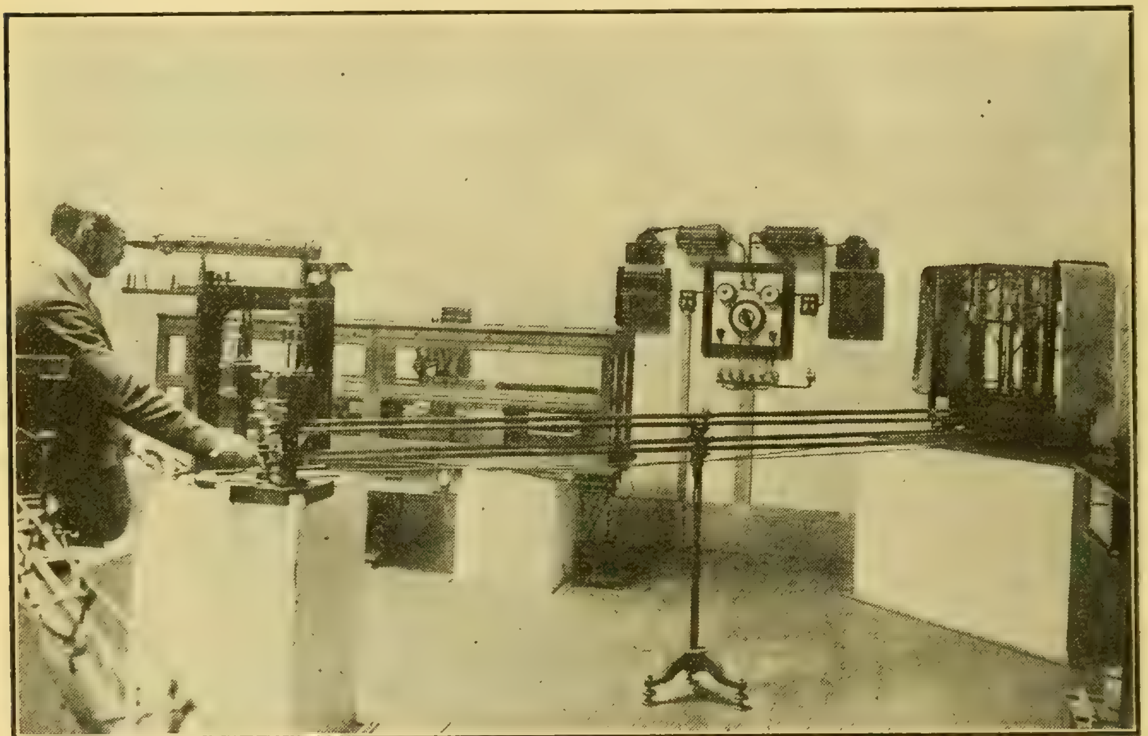
Figure 129.

Work is done in compressing the air in the tube. The air molecules have been driven into a smaller space. In this space there is a greater molecular motion — therefore more heat. Heat has been produced by the work of *compression.*

The rubber tube of an automobile tire pump gets hot because of compression when the pump is used. When the air is allowed to escape from the tire it feels cool, because it is expanding. The cooling by expansion is utilized in the manufacture of artificial ice (§ 139).

In each of these experiments work has been done. In each case, the molecules of a substance have been set into more rapid motion. *Heat has been produced by the work done* in overcoming friction, in hammering, and in compression.

83. Heat from Fuels. — Many substances produce heat when they undergo chemical changes. We say that they convert their chemical energy into heat. The most common examples of such substances are the fuels — coal, oil, and gasoline. These fuels unite with oxygen in steam boilers and in gasoline engines. Our bodies are warm (Figure 130)



© *Ewing Galloway.*

FIGURE 130. — A DELICATE BALANCE.

The temperature of the human body is about 98° F. To prevent the heat from the body from expanding the parts of this delicate balance in the Bureau of Standards, the operator handles the weights from a distance by means of long rods.

because food in the cells unites with oxygen. Wherever this process of oxidation takes place, the result is always the production of heat. When the change is completed, the chemical energy of the fuels is gone and an equivalent amount of heat is liberated in its place. This production of heat depends upon the increased molecular motion that occurs when the oxygen combines with the fuel.

84. Heat from Electricity. — When an electric current passes through a wire, the resistance of the wire must be overcome. The work done in pushing the current against this opposition sets the molecules of the wire into more rapid motion. The following experiment shows the result.

EXPERIMENT 37. — Pass a current of several amperes through a short piece of iron or nichrome wire of small diameter (B. S. No. 22). The wire becomes hot enough so that pieces of wood may be cut by it.

The electrical energy, used to move the current through the wire, produces an equivalent amount of thermal energy or heat.

Anything that sets the molecules of a body into more violent vibration thereby produces in that body a certain amount of heat. The cause of the heat may be work, or the consumption of mechanical energy; chemical changes, or the consumption of chemical energy; electricity, or the consumption of electrical energy. It is seen that when heat is produced an equivalent amount of some other form of energy disappears. *Heat may be defined as the energy of vibration of molecules.*

QUESTIONS

1. How is heat produced?

2. Mention three ways of converting work into heat.

3. Describe a case in which heat is produced from chemical combination. What is the energy condition of the products resulting from the production of heat by chemical combination?

4. Show that the conversion of chemical energy into heat is a common occurrence.

5. What substances are commonly used to produce heat by the conversion of chemical energy?

6. What practical use is made of the conversion of electrical energy into heat?

7. What change takes place in the molecular condition of a body when it is heated?

8. An iron wire may be heated by hammering it, by passing a current through it, or by burning it in oxygen. Explain each.

Expansion

The molecules of all bodies are set into more violent vibration when the bodies are heated. For most substances this means that each particle takes a little more space for its vibration, and the body as a whole becomes larger. A few substances remain practically unchanged when heated, while stretched rubber, contrary to the general rule, shrinks lengthwise when heated.

FIGURE 131. — The expanding rod rolls over the pin, causing the cardboard pointer to turn.

85. Expansion of Solids.—Although solids expand less when heated than either liquids or gases, their expansion is noticeable and can be shown experimentally.

EXPERIMENT 38. — Nail two blocks vertically to a horizontal base about a foot long (Figure 131). Groove one of the blocks halfway across the top, beginning at the inner edge. Stick a common pin through a stiff paper pointer and lay the pin on the other block. Place a brass rod in the groove of one block and upon the pin on the other block. Heat the rod by means of a bunsen flame. The pointer will revolve, showing that the rod is expanding and moving over the pin. When the flame is removed the pointer returns to its original position, showing that the rod has contracted.

Another interesting experiment that shows the expansion of solids is performed with a ring and ball (Figure 132). The

ball, when cold, just passes through the ring, but when only the ball is heated it will no longer pass through the ring. When the ring is heated to the same temperature as the ball, the ball will again pass through. In addition to showing the expansion of solids, this also shows that rings, when heated, have a larger circumference internally as well as externally.

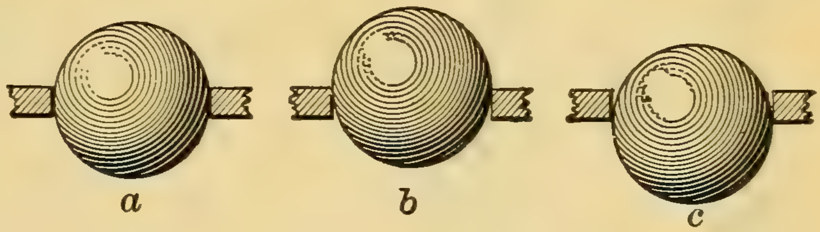
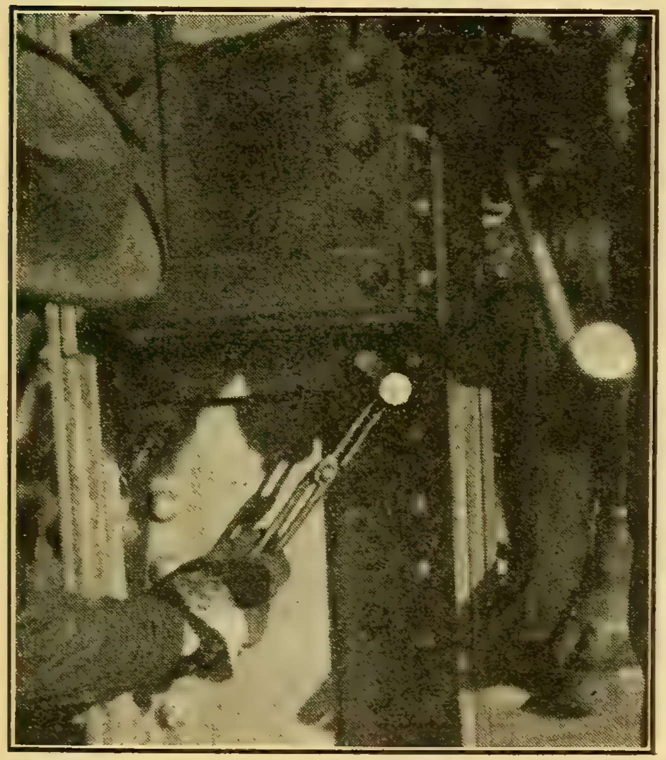


FIGURE 132. — SECTION OF RING AND BALL.
a, both cold ; *b*, ball heated, ring cold ; *c*, both heated.

86. Uses of Expansion. — The expansion of solids is sometimes useful and sometimes a nuisance. Expansion is applied usefully in the riveting of structural steel in building frames and bridges. The rivets are heated red hot and in this condition are set (Figure 133) and headed. The expansion of heating is followed by a corresponding contraction while cooling. This contraction draws and holds the parts of the structure firmly together.



Courtesy Amercian Bridge Co.

FIGURE 133. — PLACING A HOT RIVET.

The end of the rivet is hammered down into a head while hot, and the contraction of the cooling rivet draws the plates together.

It will be seen that the expansion of solids is in opposition to the

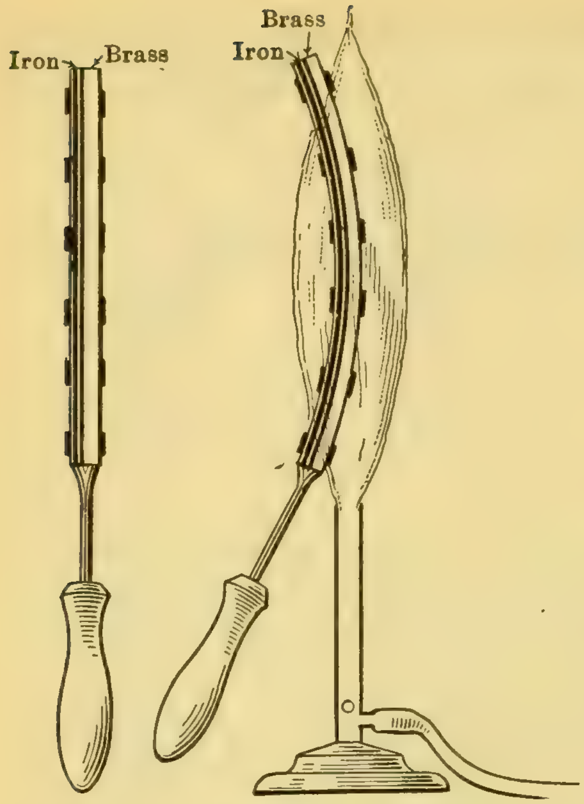


FIGURE 134. — Brass expands more than iron and makes the bar convex.

cohesion of their molecules. In solids where cohesion is strong, expansion is generally slight. The reverse of this is also true. This points to the fact that the rate of expansion (called coefficient of expansion) differs for different solids.

EXPERIMENT 39. — Fasten a strip of heavy sheet iron a foot long and $\frac{1}{2}$ in wide to a similar piece of brass, using several rivets (Figure 134). Heat this compound bar. *What change in shape takes place? Why? Which metal expands more?*

The unequal expansion of metals is usefully applied in the thermostat and in the metallic thermometer. The ther-

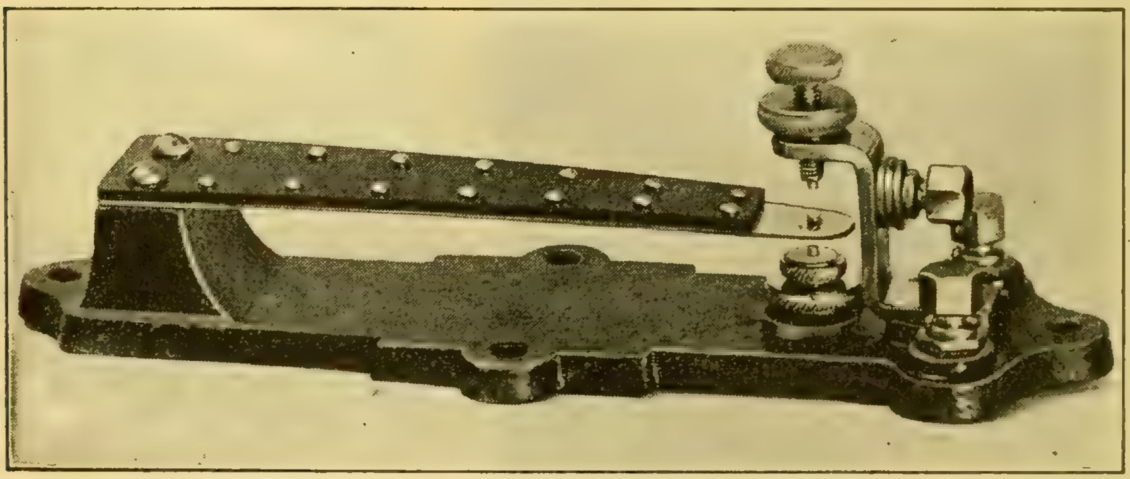


FIGURE 135. — THERMOSTAT.

The electric circuit connected to the upper contact shuts off heat and the circuit from the lower contact turns it on.

mostat (Figure 135) is used to maintain uniform temperatures in rooms remote from the source of heat. The ther-

mostat is a compound bar of hard rubber and brass. An increase in the temperature of the room causes the bar to curve slightly, due to the expansion of the brass. This movement closes an electric circuit, which shuts off the heat supply. As the room cools, the bar returns toward its first position. When the room cools to a certain degree, this movement has continued far enough to bend the compound bar sufficiently to touch the other contact and let the room receive heat again. Such a thermostat may be set to admit heat at 68° F, and shut it off at 70° F.

FIGURE 136. — METALLIC THERMOMETER.

As the temperature changes, the motion of the compound bar draws the bow-string up or down over the pivot.

The compound bar is used also in metallic (dial) thermometers. The bar is usually curved (Figure 136) with the brass on the outside. One end of the bar is fastened; the free end is attached to a string that is wrapped around an axle carrying a pointer. A rise in temperature causes the bar to curl more tightly so as to allow room for the greater expansion of the brass. The string moves the axle and the pointer revolves over a dial marked off in degrees. This thermometer has the advantage of being easily

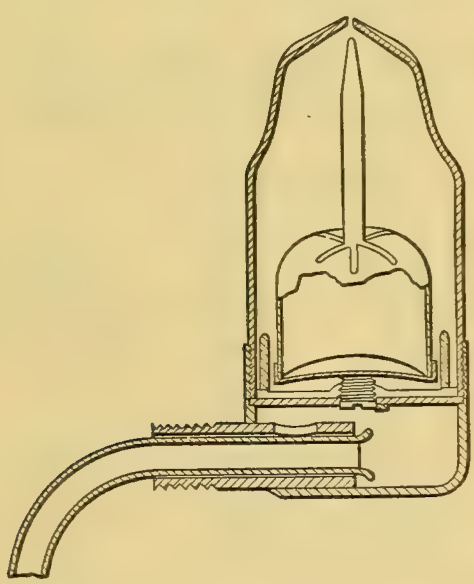


FIGURE 137. — RADIATOR VALVE

The inner bulb contains a vapor and has a flexible lid. Both the vapor and the rod are expanded by the steam.

read at a distance, and of being able to stand higher temperatures than liquid thermometers. Its disadvantage is its slow response to changes in temperature. It is also less accurate than good liquid thermometers.

FIGURE 138. — MERCURY PENDULUM.

Radiator valves (Figure 137) are devised to allow air to escape from radiators when the steam is entering, but to prevent the steam from passing out through the valve. The hot steam causes the expansion of the rod and also of the vapor in the box to which the rod is attached, thus closing the valve and preventing the escape of the steam. When the steam stops passing through the radiator, the rod and the vapor contract and the valve opens to admit air in place of the condensing steam.

87. Allowance for Expansion. — The disadvantages of expansion are numerous, and various devices are in use to overcome these disadvantages. Some of these devices make use of an expansion in one direction to overcome that in the opposite direction.

A pendulum clock depends for accuracy upon a pendulum of fixed length. When the pendulum is warm, it is too long and the clock loses time. A well of mercury is used for the pendulum bob or weight (Figure 138). The expansion of the mercury raises its center of gravity as much as the lengthening of the rod lowers it, so the effective length of the pendulum is unchanged. Other methods are also used.

Spring clocks and watches depend for their accuracy upon the regular vibration of a balance wheel attached to a hair spring. Warm weather increases the radius of the balance wheel and lessens the elasticity of the spring; both of these changes tend to make the watch lose time. To prevent this, the balance wheel is made as illustrated (Figure 139), the inside of the arcs being made of a metal which expands more slowly than the outer rim. The unequal expansion of the sides of these arcs brings the weight of the wheel nearer the center of its rotation. In this position it is easier to move and the weakening of the spring is thus balanced. The period of vibration is constant, and the watch neither gains nor loses time.

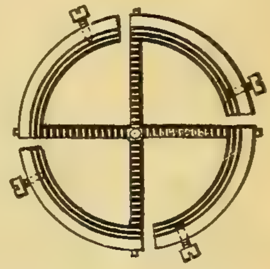
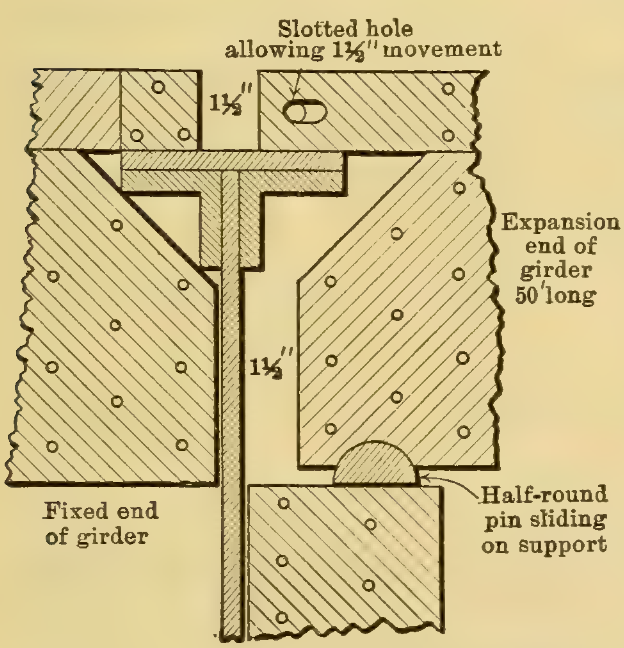


FIGURE 139.— BALANCE WHEEL.

As the spokes lengthen, the ends of the compound sections of the ring swing inward.

Allowance is made for the expansion of the rails of a car track by leaving an occasional gap between the rails. The size of this gap depends upon the temperature changes during the year. If rails 50 feet long are laid when the temperature is 50° F, they will expand about $\frac{1}{5}$ inch, if the temperature reaches 100° F, so this space must be left between the rails to prevent buckling. (What space will there be



Courtesy American Bridge Co.

FIGURE 140. — EXPANSION JOINT IN BRIDGE.

The half-round pin supporting the girder at the right slides on a base attached to the fixed girder at the left.

between the rails at 0° F?) When the rails are welded, a larger gap is left at greater intervals.

Long steel bridges expand enough to make an expansion allowance necessary. An expansion joint (Figure 140) permits the bridge to change length without injury. Another method is to rest one end of the bridge on rollers that allow the slight movement of expansion to take place without damaging bridge or supports (Figure 141).

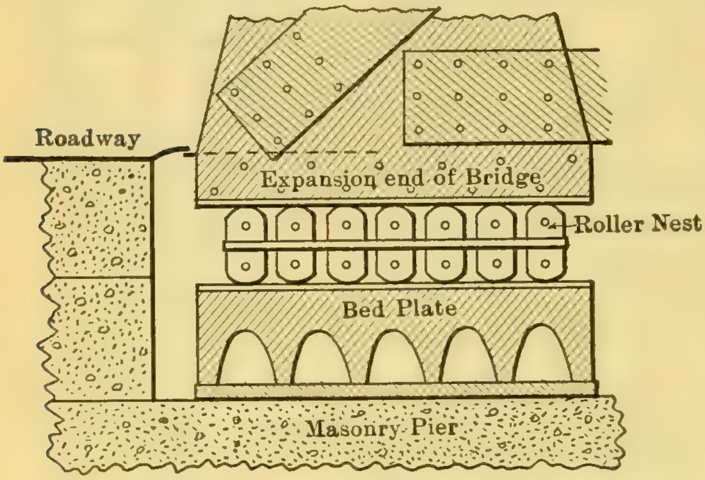


FIGURE 141. — BRIDGE SUPPORT.

The end of the bridge shown at the right can slide back and forth over the rollers resting on the bridge pier at the left.

Straight lengths of steam pipes expand so much that they must be supported by hinged metal straps (Figure 142), or else rest on rods on which they may move freely. In this way the pipes and fastenings are not injured by expansion, as they would be if they were rigidly attached to the wall.

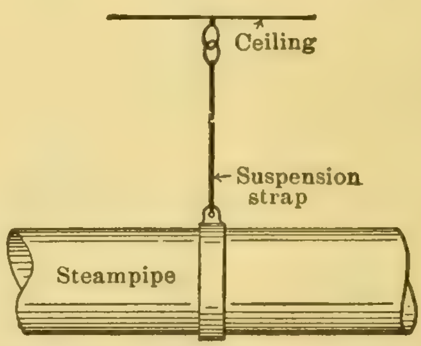


FIGURE 142. — HINGED SUPPORT FOR STEAM PIPE.

Cold glassware is likely to break if hot water is poured on it, and hot glassware breaks if suddenly chilled. The breakage occurs because a portion of the glass expands or contracts before the change in temperature has reached the adjacent portions. If all portions were heated uniformly, the expansion would be uniform and there would be no breakage. When hot water is poured into a

thick drinking glass, the inside expands before the outside is heated. The inside becomes too large for the outside and the glass breaks. If the glass is laid on its side in a pan and water poured into the pan so that both inside and outside are heated simultaneously, the glass is not likely to break. Metal vessels do not break under these conditions, because of the readiness with which the heat from the inside is passed through the wall of the vessel, thus tending to keep both sides at the same temperature. The best crucibles and flasks for laboratory use are made of spun quartz. These utensils may be heated red-hot and plunged into cold water without breaking. The quartz has so small a coefficient of expansion that it does not change in size enough to cause a break. The same principle is involved in several makes of glass baking dishes.

An alloy of 36 per cent nickel with iron is known as "invar." Invar expands very little when heated (one fourteenth as much as iron). For this reason it is used for pendulum rods, and for copies of the standard unit of length, such as the yard and meter.

88. Expansion of Liquids. — The expansion of liquids is easily demonstrated. In the same experiment the unequal expansion of different liquids can be seen.

Experiment 40. — Fill a test tube with water colored with a little potassium permanganate; fill another with alcohol colored with ink, and a third with mercury. Insert the tubes in holes bored to fit them in a board. Fit 6-inch lengths of glass tubing into 1-hole rubber stoppers and insert the stoppers in the test tubes until the liquids stand at the same level in each. Lower the tubes into a jar of hot water (Figure 143). *Where is the expansion of the liquids shown? Which expands the most? The least? What has the heat from the water done to the molecules of the liquids? Why do the liquids expand?*

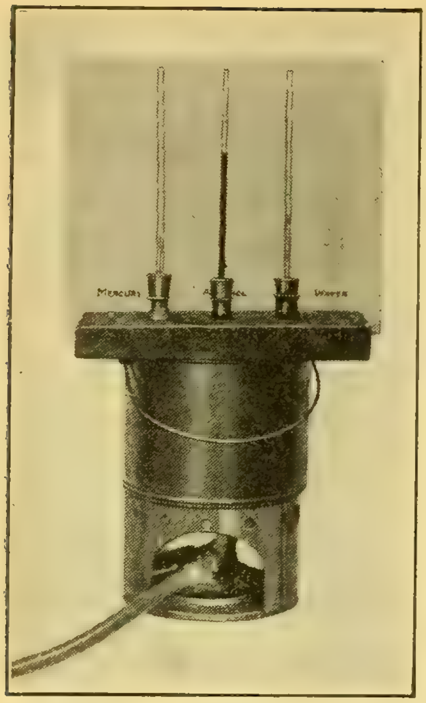


FIGURE 143.—RELATIVE EXPANSION OF LIQUIDS.

89. Rate of Expansion. — While this experiment shows that liquids expand, it only *compares* their rates of expansion. The rate of expansion of a liquid can be *measured* by putting the liquid in a bulb of known capacity. This bulb is attached to a tube of small diameter, which must also be known (Figure 144). To calculate the rate of expansion of the liquid, the rise of the liquid for a known increase in temperature must be observed; and a correction made for the expansion of the bulb. The result of the calculation would show the fractional increase in volume that a liquid undergoes during an increase of 1° in temperature.

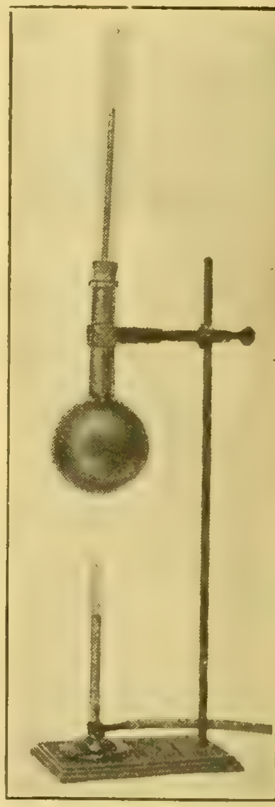


FIGURE 144.—BULB AND SCALE.

The determination of the rates (coefficients) of expansion for various liquids reveals several facts that should always be kept in mind. The first of these, indicated by Experiment 40 on page 149, is that each liquid has a different rate of expansion. A given liquid expands more rapidly at some temperatures than at others. At the temperature of freezing water (0° C) alcohol expands about $\frac{1}{910}$ of its volume if heated through one degree, but at higher temperatures the rate of expansion increases to $\frac{1}{770}$ for each degree increase in temperature. Liquids in general expand more rapidly than solids, but less rapidly than gases.

90. Effect of Temperature on the Volume of a Gas. — A toy balloon sometimes bursts when kept in the sun on a hot day. Heat expands the gas in the balloon and makes it occupy a greater volume. The glass stopper in an empty bottle is lifted up or even blown out by the expansion of the confined air when the bottle is put in hot water. Gas in a measuring tube when chilled occupies less space, as may be seen by the rise of the mercury level in a gas-measuring tube. Here a decrease in the temperature of the gas leads to a decrease in the volume.

91. Expansion of Gases. — Gases show, when heated, the greatest increases in volume of any of the states of matter. Lacking cohesion to resist the expanding effect of increased temperature, they expand readily when heated.

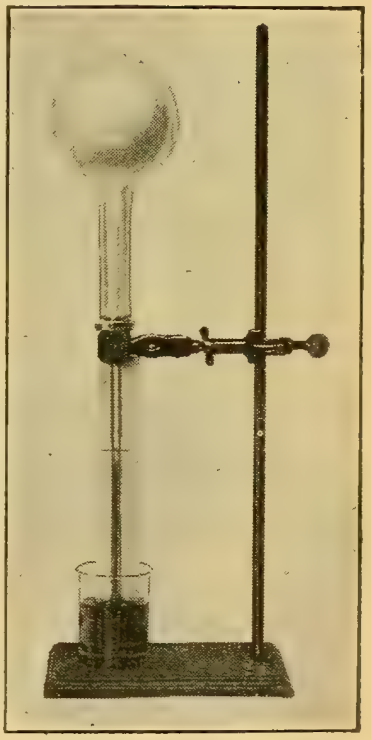


FIGURE 145. — AIR THERMOMETER.

EXPERIMENT 41. — Insert a straight glass tube in a 1-hole rubber stopper. Close the mouth of a flask with the stopper. Attach a piece of white cardboard back of the tube to aid vision, and put the end of the tube into colored water (Figure 145). Warm the flask slightly with the hand until a few bubbles come up through the water. Allow the flask to cool and water will rise in the tube. *Why?* Now warm the flask in any way. *What results? Why?* Cool the flask by wetting it and then fanning it. *Does the water level in the tube rise or fall? Why? Is the volume of the gas sensitive to changes in temperature?*

92. Rate of Expansion of Gases. — If the last experiment were performed with a flask of known volume and a tube of known diameter, the expansion of air for one degree could be calculated. The coefficients of expansion of other gases could be determined in like manner.

Such tests show that the rate of expansion is the same for all gases, because none of them has enough cohesion to check expansion. Furthermore, the rate of expansion is uniform at all temperatures.

93. Absolute Temperature. — At 0° C every gas expands $\frac{1}{273}$ of its volume for each degree through which it is heated or contracts $\frac{1}{273}$ for each degree that it is cooled. This would indicate that if the gas cooled 273 degrees it would occupy no space at all. All gases become liquids before this low temperature is reached, but the rate of contraction and other evidences point to the fact that at − 273° C molecular motion, and hence heat, cease. This temperature is known as the Absolute Zero. Absolute temperatures, reckoned from Absolute Zero, are obtained by adding 273 algebraically to the Centigrade temperature.

The relation between the volume of a gas and its absolute temperature was stated by *Charles* in a *law* which bears his name: *The volume of a given weight of gas varies directly as its absolute temperature, pressure remaining the same.* Letting V and V' represent the volume of a given quantity of a gas before and after change and T and T' the corresponding absolute temperatures, then:

$$\frac{V}{V'} = \frac{T}{T'}$$

QUESTIONS

1. Why do solids expand when heated? Why is the expansion of solids small as compared to that of fluids?

2. How may the unequal expansion of solids be shown?

3. Explain how a compound metal bar can be used as a thermostat.

4. Describe two practical uses of the expansion of a single solid.

5. Mention three cases where the expansion of solids is a disadvantage. How is the disadvantage overcome in each case?

6. What solids expand very little when heated? Where are such substances useful?

7. Describe a method of showing the expansion of liquids.

8. Do all liquids expand at the same rate? Why?

9. Describe a method of showing that gases expand when heated. Compare this expansion with that of liquids or solids equally heated.

10. Does a gas expand uniformly at all temperatures? Is this also true of liquids?

11. Define Absolute Zero. Change to absolute temperature: 42° C; – 12° C.

12. State Charles' Law. Does it apply to all gases?

13. What fraction of its volume does a gas expand, when raised from 0° C to 1° C?

14. What is the absolute temperature of a gas at 0° C? To what absolute temperature must it be raised to double its volume? To what Centigrade temperature?

15. A gas at 0° C is raised to a temperature of 25° C. Express fractionally its increase in volume.

THERMOMETRY

94. Temperature. — The word *temperature* has been used frequently in the preceding discussion. Its meaning and its measurement must now be considered. We have a rather inaccurate temperature sense which tells us whether bodies are hot or cold. The same bowl of lukewarm water, however, feels warm to a hand recently immersed in cold water and cold to a hand just withdrawn from hot water. Obviously our sense of hot and cold is not dependable. Metals feel colder than wood, even when the two have the same temperature. The words *hot* and *cold* are relative terms. A body is *hotter* than another if it can give heat to the other; it is *colder* if it takes heat when the two are in contact. As science advanced, the necessity for a fixed standard by

which the hotness or coldness of a body could be measured, became apparent.

Temperature may be briefly defined as the degree of hotness of a body. More accurately, the temperature of a body is the thermal condition of the body which determines to what extent it will give off or take in heat from surrounding objects. It must be kept in mind that heat and temperature are not the same. A cup of water poured from a kettle has the same temperature as the water in the kettle. The kettle of water has more heat, however, because there is more water. The *rate of motion* of the molecules in both cup and kettle is the same; therefore their temperatures are the same. The total *amount of molecular energy* is greater in the kettle, hence there is more heat there.

95. Thermometers. — A *thermometer* is a device to measure temperature and the measurement of temperature is called thermometry. The earliest form of thermometer was devised by Galileo. Its flask resembled that described in Experiment 41 and its inclosed air was sensitive to temperature changes. If it were not that the height of the water column varies as the atmospheric pressure changes instead of depending wholly upon temperature differences, no more accurate thermometer could be made. The regularity of expansion is so much greater than that of any liquid, that this type of instrument in a modified form is the governmental as well as the laboratory standard of accuracy.

96. Liquid Thermometers. — Although liquids, when heated, do not expand with the same regularity as gases, they are sufficiently uniform to be used where only ordinary accuracy is required. Moreover, the liquid thermometer can be read directly without adjustment, and is much more con-

venient than the more accurate gas thermometer. Mercury is the liquid usually chosen for thermometers, because of its comparative uniformity of expansion (Figure 146). Another advantage is that the boiling point of mercury is high enough (360° C) so that the thermometer may be used for moderately high temperatures, and its freezing point low enough (– 39° C) to permit it to be used for average winter temperatures in this country.

Alcohol also is used in thermometers. It is less accurate than mercury and boils at a much lower temperature; its low freezing point (–130° C) makes it desirable where low temperatures are to be measured.

FIGURE 146. — MERCURY THERMOMETER.

97. Thermometer Scales. — English-speaking people use thermometers marked with a *Fahrenheit* scale. The zero point on this scale has no present significance. The originator, Fahrenheit, thought he had reached the lowest possible temperature by mixing snow with ammonium chloride. He called this temperature "zero." On this scale the freezing point of water is marked 32°; the boiling point is 212°. The *Centigrade* scale has the two fixed points, the freezing point of water being the zero point of the scale and the boiling point being marked 100°. The Centigrade (sometimes called Celsius, from its originator) is more convenient because the simple numbers 0 and 100 mark the freezing and the boiling points of water. It is used in many countries and for many scientific purposes in this country. The scale of the Réaumur thermometer employs 0° and 80° for the fixed points.

98. Conversion of Scales. — Since zero on the Centigrade corresponds to 32° on the Fahrenheit scale, there must always exist this difference between the scales. A second difference is the number of degrees between the freezing point and the boiling point of water, 100° in case of the Centigrade scale, and 180° with the Fahrenheit. Hence each Fahrenheit degree is only $\frac{5}{9}$ of a Centigrade degree.

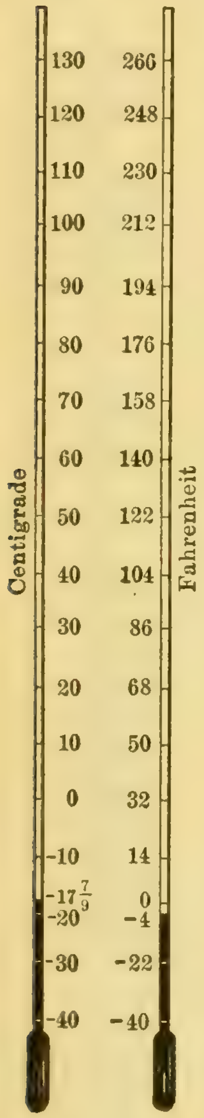


FIGURE 147. — SCALES COMPARED.

Both of these differences must be recognized in converting a temperature on one scale to the equivalent temperature on the other. Thus in changing 68° Fahrenheit to the Centigrade temperature, 32° must be subtracted from 68° to account for the difference in the marking of the freezing point of water on the two scales:

$$68° - 32° = 36 \text{ Fahrenheit degrees}$$
$$\tfrac{5}{9} \text{ of } 36° = 20° \text{ Centigrade}$$

Briefly stated, *Fahrenheit temperatures can be changed to Centigrade by subtracting 32 and taking $\frac{5}{9}$ of the result.*

To change from Centigrade to Fahrenheit, we simply reverse the process, *first multiplying by $\frac{9}{5}$ and then adding 32.* Thus in converting 15° Centigrade to Fahrenheit, the operation would be:

$$\tfrac{9}{5} \times 15° = 27 \text{ Fahrenheit degrees};$$
$$27° + 32° = 59° \text{ Fahrenheit}.$$

Figure 147 represents two thermometers marked with the two scales. When it is necessary to make a great number of conversions of temperature from one scale to the other,

a graph may be made. On this, the value on one scale can be read directly from the value of the other (Figure 148).

99. Construction of a Thermometer. — A tube of uniform diameter (Why?) is sealed to a bulb. The bulb is heated while the open end of the tube is kept beneath the surface of a dish of mercury. The air expands, and some of it bubbles out through the mercury. When the bulb cools some mercury enters. This process is repeated until the bulb and part of the tube are filled with mercury. The mercury is then boiled to exclude the air and the top of the tube is sealed by heating it. The *fixed points* are next determined. The bulb is immersed in cracked ice. The mercury is cooled and shrinks and the point where it comes to rest is marked 0° C. Immersed in live steam, the mercury rises for a time until it reaches the temperature of the steam. The highest point reached by

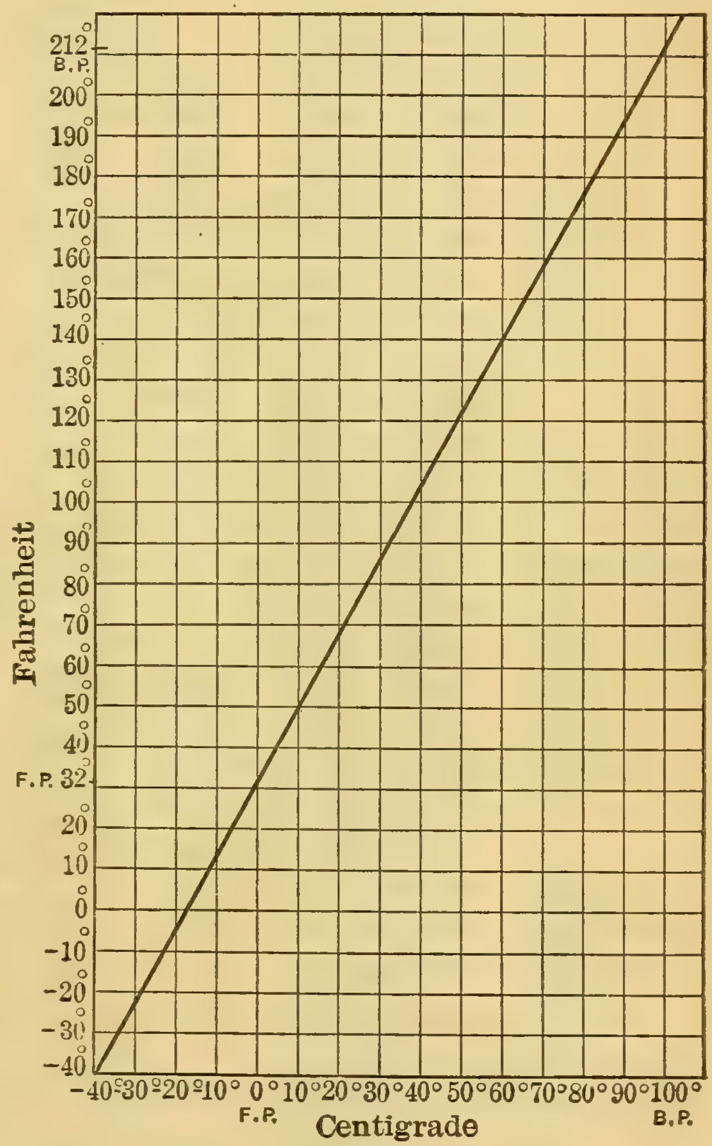


FIGURE 148. — TEMPERATURE CONVERSION GRAPH.

Find where the line of the given temperature intersects the graph and opposite this point on the other axis will be the temperature on the other scale.

the mercury thread is marked 100°, the boiling point of water on the Centigrade scale.

100. Maximum and Minimum Thermometer.—It is often desired to determine the highest and the lowest temperature during some interval of time. This is accomplished by a single self-registering thermometer (Figure 149). The tube at the right and bulb in the center are filled with alcohol. The tube and bulb at the left are filled with alcohol and alcohol vapor. The remainder of the tube, shown black, is filled with mercury. At each end of the mercury column is a light steel index that is pushed along by the mercury. The index has a spring attached to it, to make it incapable of moving by its own weight. When the alcohol in the center bulb is cooled, it contracts and the mercury pushes up the index in the right-hand tube. A subsequent rise in temperature expands the alcohol in the center bulb, pushing the mercury down in the right-hand tube and leaving the index at a point where it indicates the lowest temperature. Continued increase in temperature pushes the index up in the left-hand tube, where the index will remain at a point that indicates the highest temperature reached during the period under observation. The instrument is reset by drawing the indexes to the mercury by a

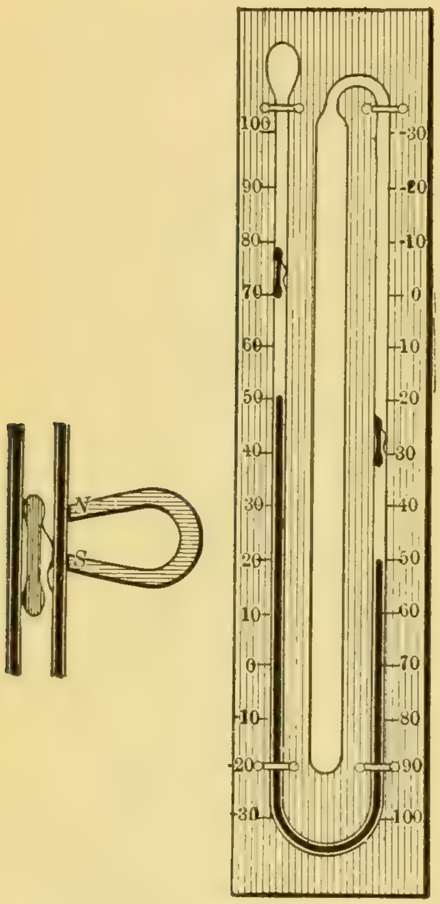


FIGURE 149.—MAXIMUM AND MINIMUM THERMOMETER.

Mercury is shown black. White bulbs and tubes contain alcohol and alcohol vapor. Method of setting index with a magnet is shown at the left.

magnet. In government stations, where weather observations are made, the instrument or a corresponding one is reset daily, and thus the maximum and the minimum temperature for each day is obtained.

101. The Clinical Thermometer (Figure 150) is a self-registering thermometer used to measure the temperature of the body. The tube is narrowed where it joins the bulb. The force of expansion pushes the mercury up through this constriction, but the weight of the mercury is not enough to pull it down through. The mercury, therefore, remains at the highest point it has reached, even after the thermometer has been withdrawn from the mouth. The bulb is thin, so that the mercury will quickly reach the temperature of the body. The tube is made small in comparison to the size of the bulb, so that a slight increase in temperature causes the mercury to move a considerable distance in the tube. It is therefore possible to read small fractions of a degree. As the average temperature of the human body in health is about 98.6° F, the thermometer is made with a range from about 94° to 110° F. It is reset by shaking the mercury down into the bulb.

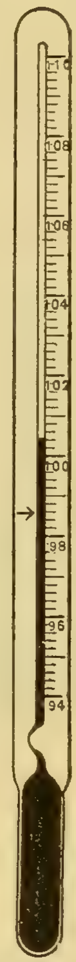
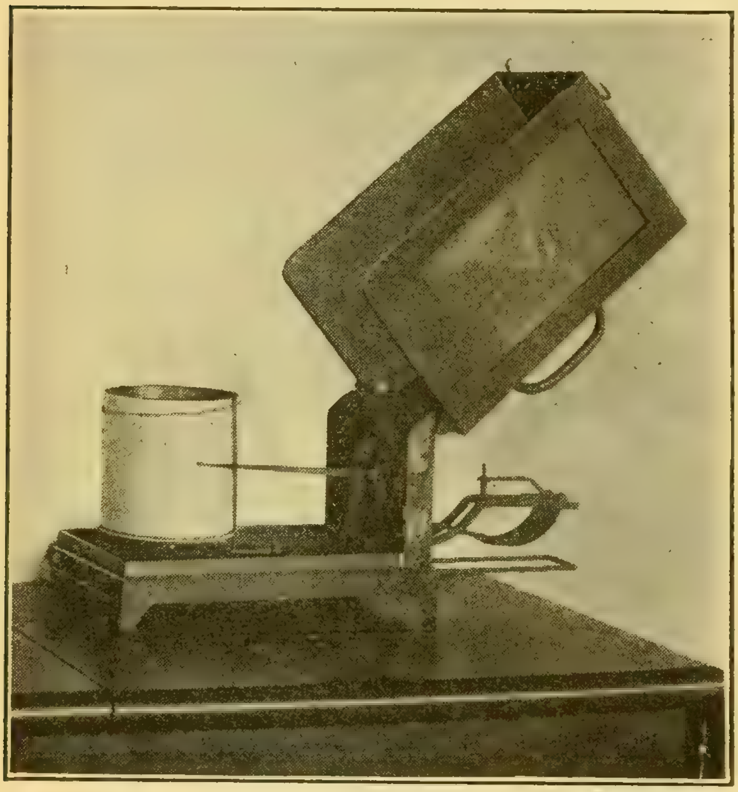


FIGURE 150. — Arrow marks normal temperature.

102. Recording Thermometers. — The ordinary thermometer shows the temperature of the place in which it is at the time of observation. The maximum and minimum thermometers show only these temperatures for some given period, but the *thermograph* records a continuous chart of

temperature changes. It registers the temperature at each instant, and this record may be read at any time after it is made. A long pointer attached to a curved compound bar (§ 86) is equipped with a self-inking pen (Figure 151). Under this pen is revolved a cylinder covered with a sheet of cross-section paper. The horizontal spaces on this paper represent time divisions, as days and hours; the vertical divisions represent degrees of temperature. As the cylinder is revolved, the pointer moves to the level that indicates the temperature at that time. The vertical movement of the pointer combined with the forward movement of the paper results in an irregular line that shows on each hour line the temperature for that hour (Figure 152).



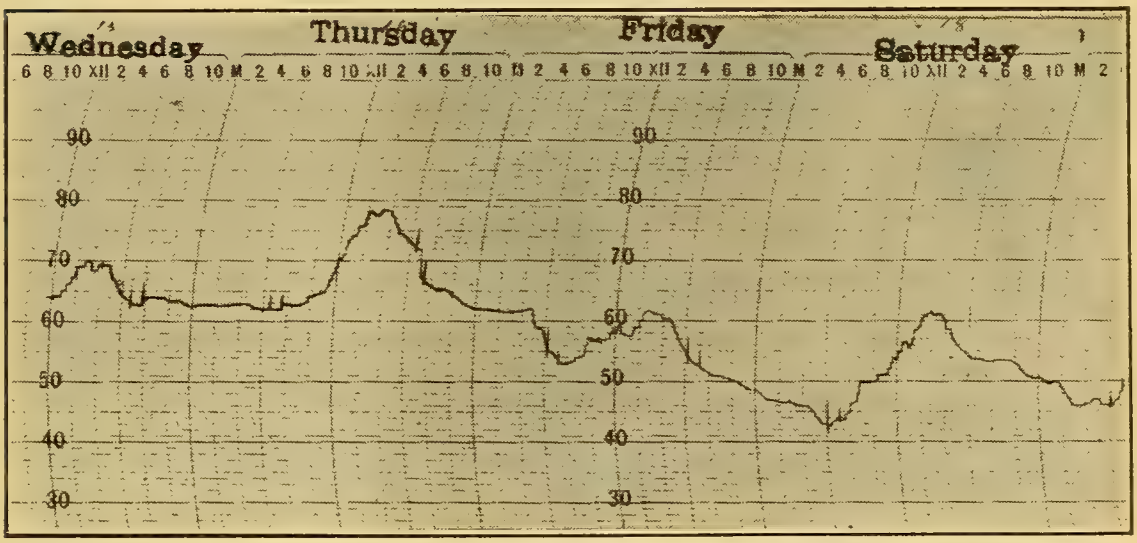
Courtesy U. S. Weather Bureau.

FIGURE 151. — THERMOGRAPH.

The small change in curvature of the compound bar at the right is magnified by the long lever, and the pen marks a continuous record of temperature on the rotating drum.

103. Irregular Expansion of Water. — Water, the most common liquid, has several characteristics that render it unfit for use in thermometers. Like many other liquids that crystallize on solidifying, water expands when it freezes. Since the freezing point of water is reached nearly every day in winter in the northern part of the United States, a water

thermometer would be useless because its bulb would break by the expanding force of freezing water. The most important reason, however, for not using water as a thermometer liquid is that its expansion is not regular. Water at 0° C actually *contracts when heated* (Figure 153). This contraction continues until a temperature of 4° C has been reached. From this point on until the boiling point (100° C) is reached water expands much as other liquids do. It is seen from the above statement that water does not occupy its least volume



Courtesy U. S. Weather Bureau.

FIGURE 152.—THERMOGRAPH CHART.

Variations in temperature for four days can be followed in detail.

when at its lowest temperature, hence it cannot be used in thermometers.

The significance in nature of the peculiar expansion of water is worth investigating. In autumn, the water in a pond cools by giving its heat to the colder air above it. As the upper layer of water thus cools, it contracts and sinks to the bottom because it is denser than any other water in the pond. This process is repeated until all the water in the pond has circulated from top to bottom and back several

times. Eventually a quantity of water is cooled to 4° C. It sinks to the bottom, but cannot be displaced by a colder layer, because the colder layer cannot be denser than water at 4°. All the water in the pond is thus cooled to this temperature. Now when the topmost layer of the water is cooled, it expands and thus becomes lighter as water does in cooling from 4° C to 0° C. This layer remains at the top of the pond, cools still more, and then freezes. With a coating of ice over the water, heat cannot be given off rapidly by the water, and so the water under the ice cools and freezes slowly. If water continued to contract as it cooled to the freezing point, all the water in the pond would reach the freezing temperature and shallow ponds would be frozen solid every winter if temperatures lower than freezing were common. In a pond of any considerable depth, the temperature just under the ice is 0° C; at the bottom it is 4° C; the temperatures between top and bottom will vary between these limits.

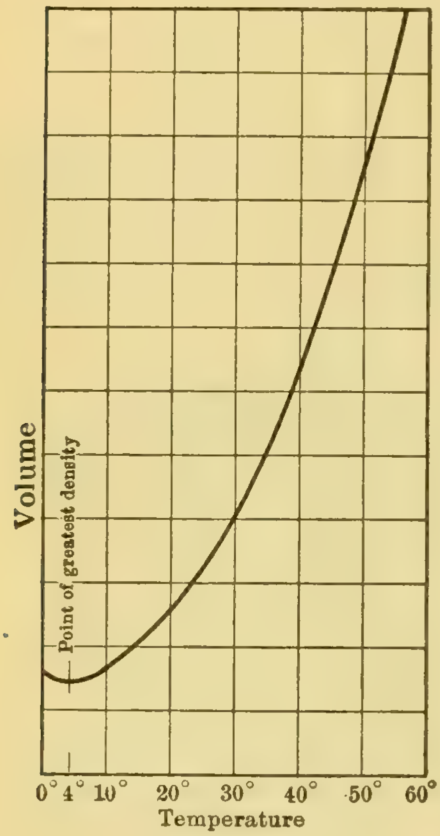


FIGURE 153. — EXPANSION CURVE OF WATER.

The volume is shown decreasing to 4°, then increasing, first slowly and then more rapidly.

QUESTIONS

1. Make clear the meaning of the word *temperature*. Distinguish between temperature and heat.

2. What liquid is usually selected for an accurate thermometer? Give two reasons for this choice.

3. Describe the construction of a mercury thermometer.

4. Why is alcohol used for thermometers? Are alcohol thermometers more or less accurate than mercury thermometers?

5. Compare the two common thermometer scales as to fixed points, size of degree, and usefulness.

6. Describe the method of converting temperatures of one scale to the equivalent temperatures on the other scale.

7. During a cold wave a Fahrenheit thermometer showed a decrease of 27 degrees in six hours. What would be the corresponding change on a Centigrade thermometer?

8. Soft candies are cooked until a boiling point of 238° F is reached. What would a Centigrade thermometer indicate?

9. Find the Fahrenheit temperature of Absolute Zero (−273° C).

10. Find the Centigrade temperature of bath water which is 115° F.

11. Find the Centigrade temperature of the body (98.6° F).

12. Alcohol of a certain purity boils at 80° C. Find the boiling point of the alcohol on the Fahrenheit scale.

13. Water is at its greatest density at about 4° C. Find the corresponding Fahrenheit reading.

14. What are maximum and minimum thermometers?

15. What is a clinical thermometer? Explain the operation of a clinical thermometer.

16. Describe the volume change of water from 0° C to 100° C.

17. Of what importance is the irregular expansion of water?

SUMMARY

Heat is necessary for life; civilization has progressed as man has improved his control of heat.

Heat is produced only by the conversion of some other form of energy.

Any form of energy may be converted into heat energy: heat energy may be changed into any other form of energy.

Mechanical energy may be converted into heat. Examples of this conversion are seen in the compression of air and in overcoming friction.

Heat may be produced by the conversion of **chemical energy.** Foods and fuels are oxidized to produce heat. The chemical energy lost by oxidizing these substances appears as heat.

Electrical energy is converted into heat in lamps and heaters of various sorts.

Nearly every substance becomes larger when heated. This **expansion** is opposed by cohesion, hence is least in solids and greatest in gases. **Contraction** during the cooling of heated solids is used in riveting, in setting iron wagon tires, and in many other cases.

Metals differ in their rates of expansion. Use is made of this in thermostats, timepieces, and dial thermometers.

The expansion of solids is often a **disadvantage** for which allowances must be made. The breaking or buckling of heated objects results from expansion.

Liquids expand to a greater extent than solids when heated. Liquids vary in the rate at which they expand. A given liquid may expand at various rates according to temperature. **Water** contracts from 0° C to 4° C and then expands up to its boiling point.

Gases expand almost uniformly at all temperatures, and all gases expand at the same rate.

Absolute temperatures are calculated from Absolute Zero, − 273° C. **Charles' Law** states: The volume of a given weight of a gas varies directly as its absolute temperature, pressure remaining the same.

Temperature is the degree of hotness of a body. Temperature is measured by a thermometer which makes use of the expansion of some substance, usually a liquid, when it is heated.

The fixed points on a thermometer are the boiling point and the freezing point of water at normal pressure. The two scales used, Centigrade and Fahrenheit, have 100 and 180 degrees respectively between these two points.

If 32 degrees be subtracted from any Fahrenheit temperature, $\frac{5}{9}$ of the remainder will be the equivalent Centigrade temperature. If $\frac{9}{5}$ of any Centigrade reading be taken, and 32 be added to the result, the equivalent Fahrenheit temperature is obtained.

EXERCISES

1. Why are sparks seen when brakes are applied to car wheels? What energy is caused to disappear?

2. What is a "hot box" and how is it caused?

3. In colonial times, flint and steel were used to start a fire, or to explode powder in a gun. Explain.

4. Although friction is slight in a tire pump, the cylinder and tube become heated when used. Explain.

5. In artificial refrigeration, some gas (ammonia or carbon dioxide) is liquefied by compression. What heat change takes place during compression?

6. After the gas is compressed, it is allowed to vaporize. What heat change takes place during this process?

7. What substances are valuable because their chemical energy is easily converted into heat?

8. Why do explosions of gas, gasoline, gunpowder, and similar substances produce great pressures?

9. Should the pendulum of a clock be lengthened or shortened in the summer? Why?

10. A piece of iron that is to fit tightly over another piece is heated before being fitted into place. Explain.

11. How could a compound bar and an electric bell, battery, and contacts be used as an alarm to indicate the approach of freezing temperatures in a fruit warehouse?

12. Why is a tube of small bore used in an ordinary thermometer? Why must the bore be uniform throughout?

13. What characteristics must a liquid have in order to be suitable for use in a thermometer?

14. Describe the method by which a thermostat regulates temperature.

15. What temperature would be found just under the ice in a frozen pond? At the bottom of the pond? Explain.

16. Glass stoppers that fit too tightly to be removed easily may be started by rubbing the neck of the bottle briskly with a single turn of stout cord. Explain.

17. Furnace grates are made to fit loosely. Explain.

18. Why is a water thermometer impracticable?

19. What is the chief defect of a simple air thermometer?

20. Why is a narrow tar-filled space left at frequent intervals in brick and cement pavements?

21. What purpose is served by lubricating machinery other than to make it easier to operate?

22. Why are most automobile engines equipped with a water jacket, placed around the cylinder so as to cool the engine?

23. Why is it necessary for a watch to be adjusted for changes in temperature? How is this adjustment made?

24. Glassware is likely to break if its temperature is suddenly changed. Why is this so?

25. What characteristics has the Centigrade thermometer scale which make it desirable for scientific use? Is it desirable for household or clinical use?

26. Why are slanting roofs seldom covered by a continuous sheet of metal, although the use of small metal shingles is common?

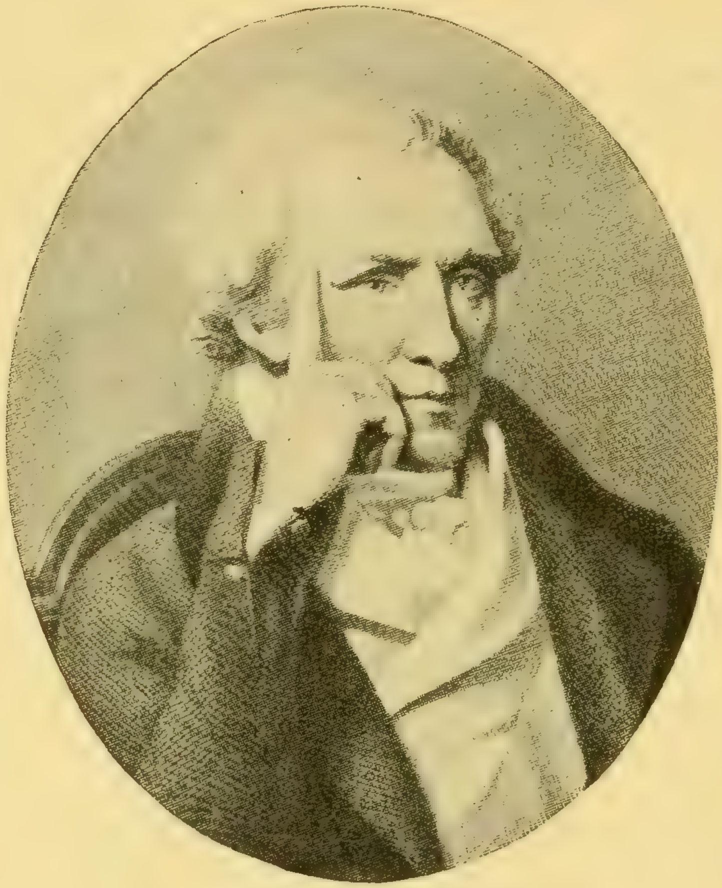
27. What is the effect of the sudden changes of temperature at high altitudes upon exposed rocks?

28. What causes paper Fourth-of-July balloons to rise?

29. If a pebble wedges in a rock crevice, what effect will it have upon the walls of the crevice, if it warms more quickly than they? If it cools more quickly at night, what will it do?

30. A liter of gas at 10° C is heated at constant pressure to 25° C. What volume will it occupy at 25°?

31. What theoretical volume would a gas occupy at Absolute Zero? Why does the gas fail to contract to this extent?



Benjamin Thompson, Count Rumford (1753–1814) was an American by birth who fled from the colonies as a tory during the Revolutionary war. From England he went to Bavaria and held a number of important offices under the Elector. He was a practical scientist and did a great deal of work in improving methods of heating, lighting, cooking, and other things which would better the condition of the poor. In theoretical science he is famous for the conception of the idea that heat is not a material substance but a motion within the heated body. This idea was developed by Davy, Helmholtz, Joule, Tyndall, and others.

CHAPTER X

HEAT AND ITS TRANSMISSION

104. Nature of Heat. — Air in an automobile tire causes a blowout, if the air is heated too much by the friction in the tire. The air in the bulb of an air thermometer pushes harder on the liquid when the bulb is heated. In both cases, a certain number of molecules, when they are heated, press harder against their container. Since the number of molecules does not increase, each molecule must strike a harder blow, because it is moving faster. The explanation of the nature of heat is based upon this increased molecular motion.

Heat was produced, transmitted, and used centuries before its nature was adequately understood. Only rarely does a man appear who has enough scientific curiosity to try to explain everyday occurrences. An American, usually known by his foreign title of Count Rumford, is credited with the first workable explanation of the nature of heat. Rumford was in the service of the Elector of Bavaria and, among various duties, superintended the boring of brass cannon. He noticed that much heat was generated by this operation. He immersed the cannon in a water jacket and found that the water surrounding the cannon was heated to boiling.

105. Kinetic Theory. — Rumford's experiments and observations led him toward the development of a new theory of heat. A number of other scientists were soon working on the same problem. Sir Humphry Davy discovered that ice could be melted by rubbing pieces of it together

even at a temperature below freezing. Joule's experiments proved that when a given amount of work was done a fixed amount of heat was produced. Tyndall, Helmholtz, and Maxwell developed the theory further by experiments and reasoning.

The result of the work of these men pointed to the following explanation: *The molecules of all bodies are in motion to an extent that depends upon the temperature. The energy of the moving particles constitutes the heat of the body.* An increase or decrease in the molecular motion within the body means an increase or decrease in the heat possessed by the body. Molecular motion, and hence heat, are supposed to cease at Absolute Zero, $-273°C$.

Two experiments will show the relation between heat and motion. The pupil must understand that a theory cannot be absolutely proved by experiment, but that an experiment may give evidence of the truth of a theory.

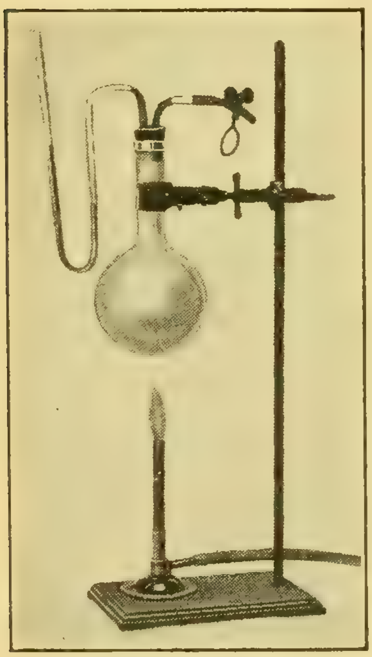


FIGURE 154.

EXPERIMENT 42. — In a test tube a small quantity of mercury is placed. The mercury is covered with small bits of broken colored glass. The air is then exhausted from the tube and the tube sealed. Now heat the mercury until it boils. As its molecular motion increases with heat, the glass fragments, struck by the rapidly moving mercury molecules, will be driven up into the space above the mercury.

EXPERIMENT 43. — To a glass flask attach a simple mercury manometer (Figure 154). Heat the flask by a bunsen flame. *What change in pressure is indicated by the manometer? Since there are no more molecules of air in the flask than before, how do you account for the change in pressure?* Open the pinchcock and let the pressure equalize, then close the pinchcock. Cool the flask by sprinkling water on it. *What pressure change is shown by the manometer? What do you infer concerning the motion of molecules?*

QUESTIONS

1. What names are associated with our present theory of heat? What contribution to the theory was made by each man named?

2. What experience led Rumford to believe that heat is a form of energy?

3. What is the nature of heat?

4. What experiment could be performed to show the relation between heat and molecular motion?

5. Why do gases expand when heated under constant pressure?

6. Why does a liquid vaporize when heated sufficiently? How does the motion of molecules of a liquid compare with that of its vapor at the same temperature?

7. Why does water freeze when its surroundings are cold enough?

8. What change takes place in the molecular motion when water freezes?

9. A kettle filled with liquid air boils vigorously when set upon a cake of ice. How does the molecular motion of the ice compare with that of the liquid air?

10. How do the molecules of the ice affect those of the kettle containing the liquid air? How do the molecules of the kettle in turn affect those of the liquid air?

11. Is there a theoretical temperature at which molecular motion is thought to cease? How closely has this temperature been approached?

12. What is the condition of the gas inside an automobile cylinder while the explosion is occurring? Does this gas possess energy?

13. In what way does a hot body differ from a cold one?

106. Transmission of Heat. — The apparent ease with which objects gained or lost heat deceived the ancient philosophers into the belief that heat was a weightless fluid that entered or deserted the body as its temperature changed. We know now that heat energy may be taken from or added to a body by only three different methods of transmission. To these three methods we apply the names *conduction, convection*, and *radiation*.

107. Conduction of Heat. — The conduction of heat is best studied by an experiment.

Experiment 44. — Support a brass rod horizontally and on it slip several paraffin rings evenly spaced (Figure 155). Heat one end of the rod. *Which ring melts off first? Why? What has happened to the molecules of brass at this ring? Why do you suppose this to be true?*

We are led to the conclusion that the molecules at the heated end of the rod are set into violent agitation by the flame. The bumping of these molecules against their cooler, less active neighbors has started them moving more rapidly. Thus increase of molecular motion, *i.e.* heat, has passed slowly along the rod. *Conduction is the transfer of heat from a hot body to a cold body by molecular collision.* The molecules must be in contact.

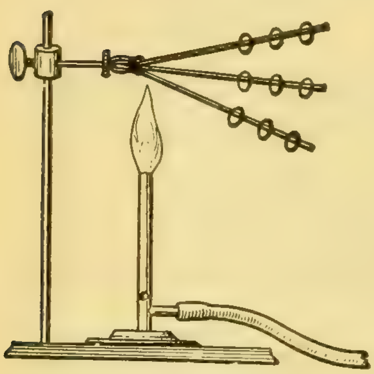


Figure 155.

108. Conductivity of Different Substances. — Early in life we acquire a working knowledge of the relative conductivity of various substances. For example, we know that cloth or paper may be safely used to pick up warm metals, and we trust that the wood handles on pot lids and kettles will not be hot enough to burn us. The difference in conductivity of other substances may be seen from the following experiment.

Experiment 45. — In a manner similar to the previous experiment, support rods of brass, iron, and glass so that one end of each may be heated simultaneously and equally (Figure 155). Hang a paraffin ring on each, at an equal distance from the flame. Heat the rods until two of the rings have fallen. *Which substance is the best conductor? The poorest? In general are metals or non-metals the best conductors?*

Liquids and *gases* conduct heat scarcely at all.

EXPERIMENT 46. — By means of a coil of wire, hold a piece of ice at the bottom of a long test tube of water. Slant the tube and heat it carefully near the top until the water boils there (Figure 156). *Why does not the ice melt? What means of heat transference seems to be lacking in water?*

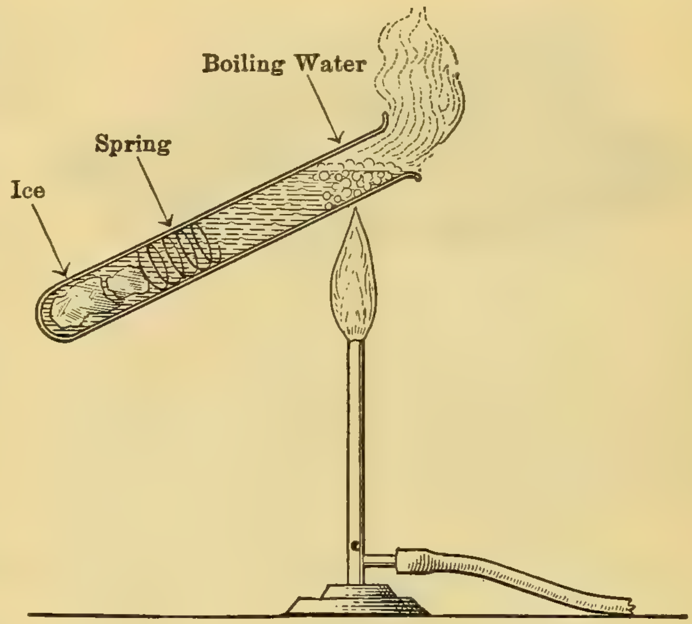


FIGURE 156.

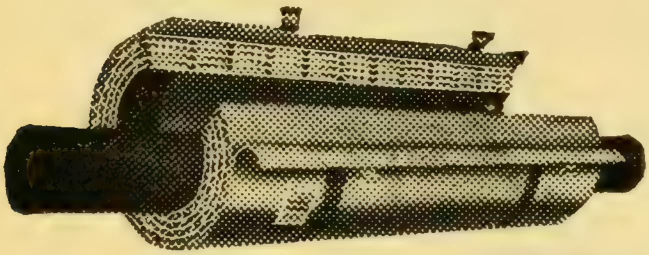
Efforts to test the conductivity of gases are complicated by the fact that heat is transmitted in gases by other ways than conduction. We know, however, that we can bring the finger very near a hot iron without danger of a burn. This we could not do if the air between the iron and the finger were a good conductor. We can even hold the hand within a fraction of an inch of a very hot bunsen flame without injury because the air between is practically a non-conductor (Figure 157).

FIGURE 157.

A review of the previous paragraph shows that conduction is restricted almost entirely to metals. Most non-metallic solids and all liquids and gases are poor conductors; they are heat insulators.

109. Useful Conduction.—The examples of useful conduction of heat

are numerous and important but not conspicuous. As the tip of a soldering iron and the bottom of a flatiron are cooled by use, heat is *conducted* from their hotter portions to the cooled surfaces. Heat passes by conduction through the iron radiator to the outside; through the bottom of the kettle of water over the fire; and through the iron shell of the steam boiler to the water inside. In fact, there is no other method by which heat may be transferred *through* a solid. It may be seen that most of our cooking and heating processes depend in part upon the transmission of heat by conduction, although the distance through which the conducted heat travels is always small.



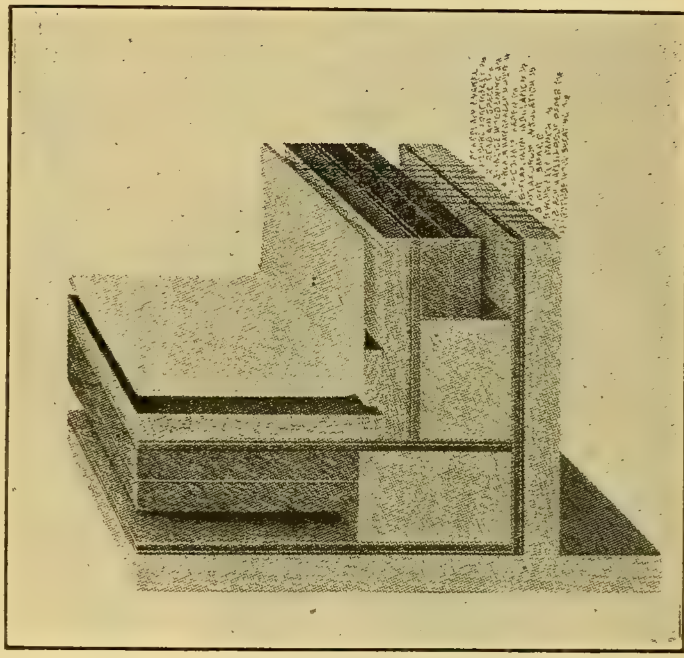
Courtesy Johns-Manville Co.

FIGURE 158.—The covering is partly laid back to show its structure. The corrugated asbestos paper, itself a poor conductor, encloses small bodies of air—a still better insulator.

110. Useful Insulation. — The prevention of heat losses or transfers is often of great importance economically. Such losses or transfers are prevented by the use of insulators of fibrous or granular structure, of which asbestos cloth, packed hair, felt, mineral wool, powdered cork, and sawdust are good examples. The value of these substances lies in the dead air spaces between the fibers. As previously noted, air is an excellent insulator against heat conduction, and, if it is held stationary by the fibrous material, little heat will pass through such material. Steam pipes are coated with a layer of one of the above insulators (Figure 158); ice boxes (Figure 159) and ice houses have double walls with one of the insulators as a filler between the walls. Carpets, bed clothing, garments, furs, and the like all depend for their

usefulness as insulators upon the dead air held between the fibers. Linen, the fabric which has the largest fibers and the fewest air spaces, is the coolest material for clothing. Its opposite is wool or fur with many air spaces between its fibers.

It is of interest to note that good conductors, such as metals, *feel* cold to the hand if they *are* colder than the hand. They feel very hot if warmer than the hand. In the first case they conduct heat rapidly *from* the hand and make it cold. In the second case, they conduct heat from a large adjacent area of the metal *to* the hand. Insulators, such as wood or the carpet on the floor, do not feel so cold to the flesh as metal or tile, because they do not conduct much heat away from the body. The portion in contact with the body is quickly warmed and does not lose much heat to adjacent portions.



Courtesy Bohn Syphon Refrigerator Co.

FIGURE 159. — WALL SECTION OF PORCELAIN LINED REFRIGERATOR.

There are two air spaces and several layers of paper, wool felt, and other insulators.

111. Convection. — We naturally hold our hands *over* a fire or radiator to warm them. Light objects like paper, dust, and smoke show that there is a strong current of warm air upward over any source of heat. Warm air is streaming upward from the source of heat to some colder place, which will be warmed by this rising current. *Convection*

currents are easily made and can be studied by a simple experiment.

EXPERIMENT 47. — Cut a 5-inch circle of sheet iron nearly to the center, making 30-degree sectors. Bend these sectors slightly to form a windmill. Mount the disk on a pointed rod set into a tiny dent at the center of the disk, and bent out so that the blades on one side can be held over a bunsen flame (Figure 160). The disk will be pushed rapidly around by the upward current of hot air over the flame. This current may be shown by holding the bunsen flame in front of an arc lamp that illuminates a white surface (Figure 161).

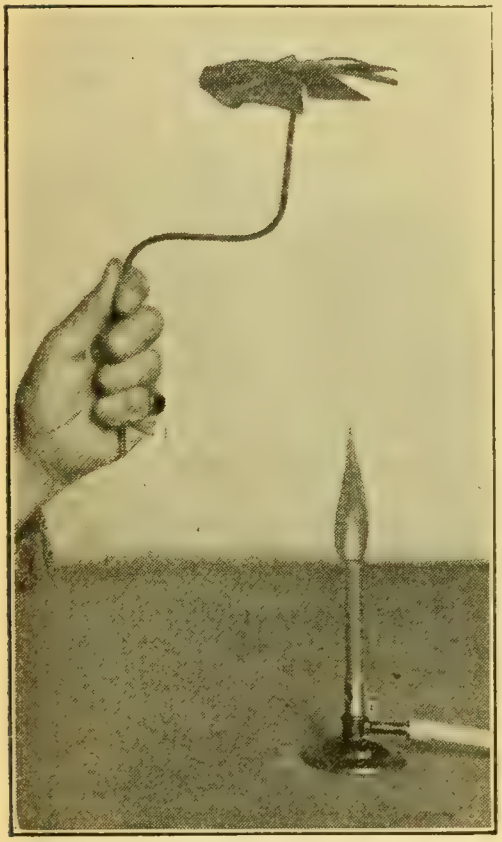


FIGURE 160. — The spinning of the wheel shows rising air currents.

EXPERIMENT 48. — Fit a flask with a 2-hole stopper in which are set two tubes, as shown in Figure 162. Fill this flask with water colored by ink, or otherwise. Heat the flask on wire gauze over a flame, until the water is nearly boiling. By means of a wire, lower the flask into a deep jar of cold water. *What motion of water takes place? Why? How long do you think this current will continue? Why does the colored water sink after rising? How will the temperature of the water in various parts of the jar and flask compare after convection has stopped?*

The earlier parts of this chapter state that the molecules of a heated gas travel more rapidly as the temperature of the gas is raised. This means that the molecules spread out to occupy more space, *so the density of the gas is decreased.* A liquid behaves in a similar way. The gas or liquid, thus made lighter, has a downward pressure less than the colder air or water beside it, and is therefore pushed up by the denser fluid. The rising column carries its heat along and loses it in some colder region.

Convection is the transfer of heat by moving currents of a fluid.

112. Useful Convection. — Convection of heat has been man's chief method of distribution of heat produced by his fires. Primitive cooking was done *over* a fire to

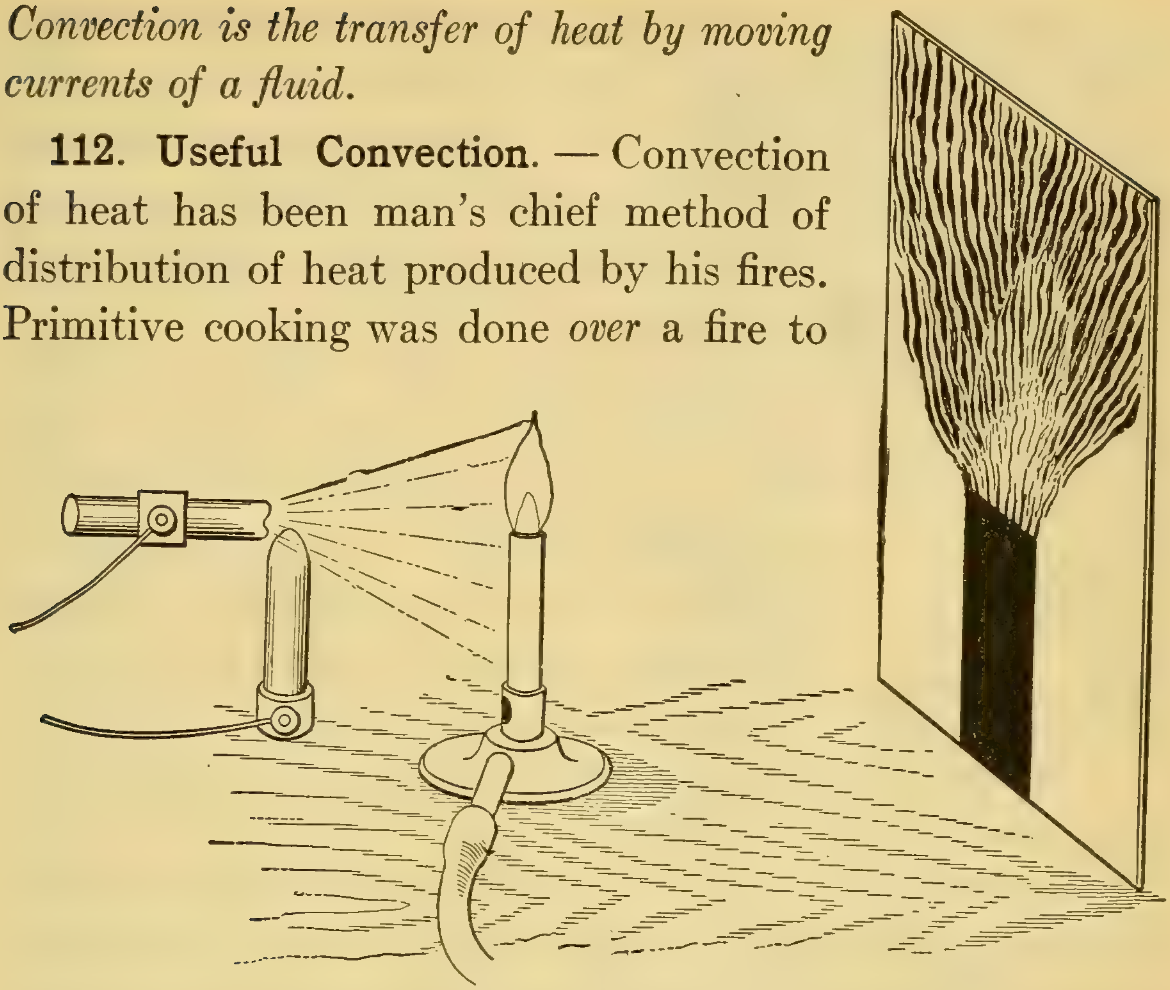


FIGURE 161. — CONVECTION CURRENTS IN AIR.

Changes in the density of the air cause it to transmit light from the arc differently.

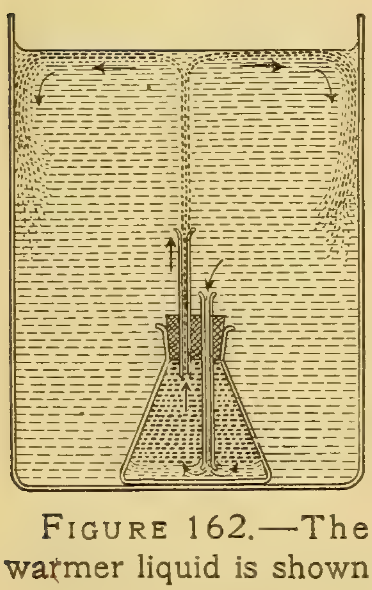


FIGURE 162.—The warmer liquid is shown by dark shadowing.

make use of convection currents. Later, man supplied a chimney for his fireplace and thus got rid of the smoke (Figure 163), furnished a better supply of oxygen for combustion, and incidentally lost much of his heat up the chimney. The gain, however, overbalanced the loss; and chimneys, which are simply convection pipes, are in use with every fire where smoke is to be removed and oxygen furnished.

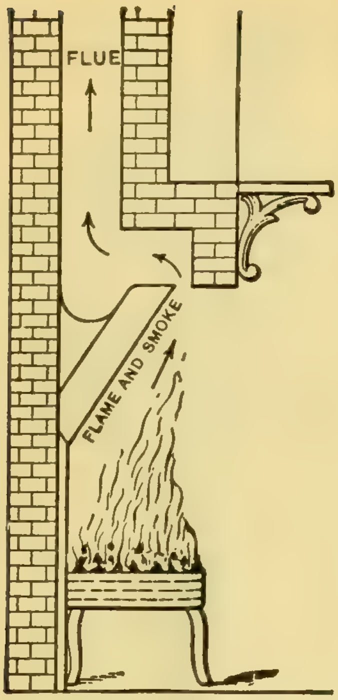


FIGURE 163. — FIREPLACE.

Arrow shows direction of currents.

Water in a kettle is heated throughout by convection currents, as shown in Figure 164. These currents will bring all the water to the same temperature before they stop, unless outside causes interfere.

Ice in refrigerators is placed as near the top of the ice box as is convenient so as to be above the food to be cooled. A *downward* current of cold air cools the food in the lower compartment, while an ascending current of warm air from the food melts the ice (Figure 165). Prevention of convection would make the refrigerator useless.

We see now the necessity for some fibrous material (§ 110) to hold air stationary, when conduction is to be prevented. Air is an excellent insulator if kept at rest, but unless held between solid fibers, it tends to set up convection currents that transfer the heat too readily.

113. Stoves. — When larger houses came into use, convection currents of steam, hot air, or hot water were utilized to transfer the heat from one central source to distant parts of the house. The stove heats one or more rooms largely by convection. Warm air over the stove is pushed up by the colder air on the side. This warm air cools as it spreads out at the ceiling, becomes denser as it cools, falls as it becomes denser, completing the circuit

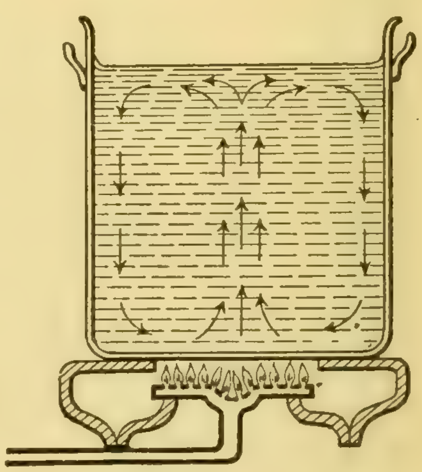


FIGURE 164. — By making the burners smaller than the bottom of the kettle, definite convection currents are secured.

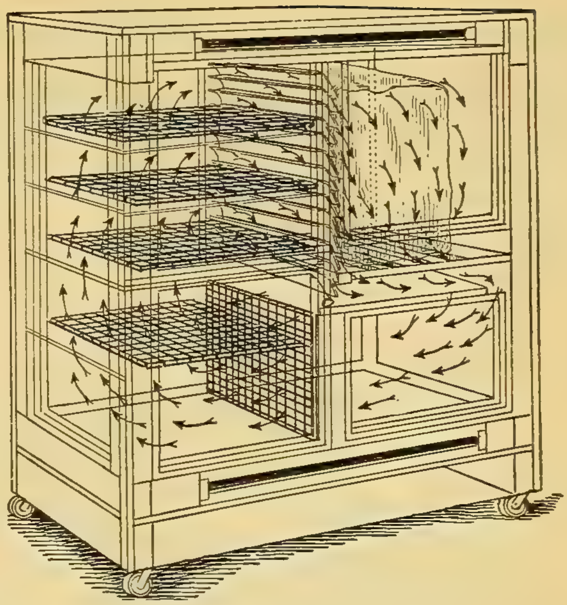


FIGURE 165. — ICE BOX.

The doors have been omitted and the walls drawn light to make the convection currents clearer.

by moving toward the stove to be reheated (Figure 166). If the fire goes out, convection will continue until all the air in the room is at the same temperature. Usually the ceiling is warmer than the floor, because of the strong upward currents of warm air, and because cool air, leaking in through cracks, always settles to the floor.

114. Hot-Air Heating. — Hot-air furnaces are often used in single houses. An air compartment is placed over the fire pot of the furnace. The air is heated, expands, is pushed up through pipes to the various rooms and heats them. A cold-air flue admits a constant supply of fresh air to be heated and thus furnishes a valuable ventilating feature for this kind of furnace. Sometimes from motives of economy, the cold air is removed from the floor of the lower rooms by a flue that leads to the air compartment. In the recently developed "pipeless" or "one-pipe" furnaces (Figure 167), cold air thus settles through the outer portion of a single register and is reheated to rise again

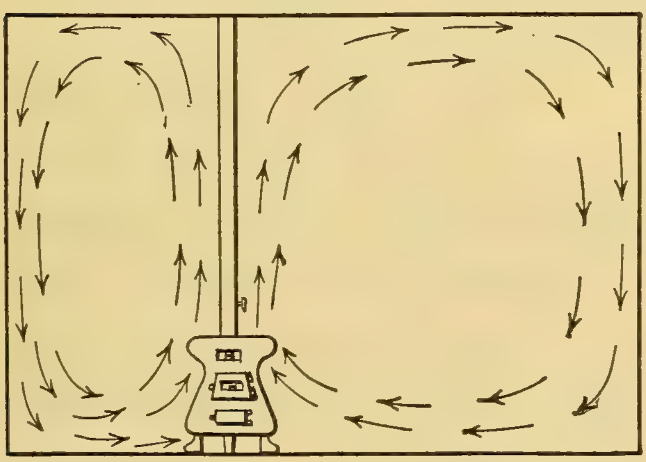


FIGURE 166. — HOW A STOVE HEATS A ROOM.

through the inner portion of the same register. Naturally, less coal is required to reheat the partially cooled air of the house than to heat fresh cold air from outside. Claims for greater economy are based upon this fact.

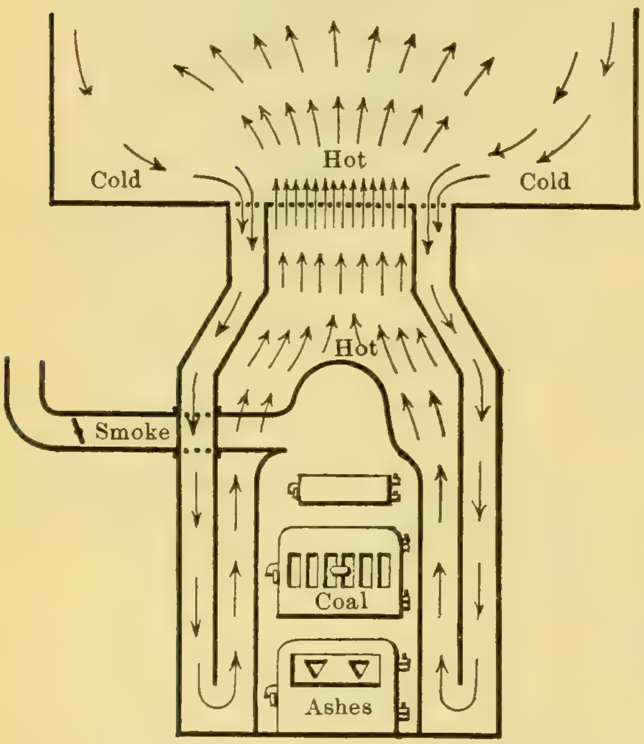


FIGURE 167. — A PIPELESS FURNACE.

The exchange of temperatures between the two air streams prevents the air entering the room from being too hot. The descending cool air reduces the loss of heat to the cellar.

115. Hot-water Heating. — A hot-water heating system (Figure 168) utilizes water as the hot-air system uses air. Riser pipes leave the top of the water space of the heater and admit rising streams of hot water to radiators in the several rooms. The water in the radiators cools by giving off its heat to the rooms. As the water cools, it becomes denser and sinks through return pipes to the bottom of the water space to be reheated. The entire system must be full of water at all times. An expansion tank, above the highest radiator, allows the water to expand as it is heated. This system, like the hot-air system, starts convection currents when the fire is started. These currents continue as long as there is any inequality of temperature in the system. This permits an easy regulation of the temperature of the house.

Hot water for kitchen and bath is heated in a similar way (Figure 169). In this case, however, the circulation of the

hot water through the house is caused by the pressure of the city water system.

116. Steam Heating. — Large buildings and many small houses are heated by steam systems (Figure 170). A boiler partly full of water is used instead of the full tank in the hot-water system. When the water in the boiler is heated to boiling, the pressure of the steam forces the steam up the riser pipes to the radiators, where it gives off its heat of vaporization (§ 130), condenses, and returns as water either by the riser pipes or by separate return pipes. Steam systems are cheaper to install than hot-water systems, for they require less boiler capacity, smaller radiators, and not necessarily a return pipe. In the steam system the distribution of heat is also somewhat more certain than in the hot-water system.

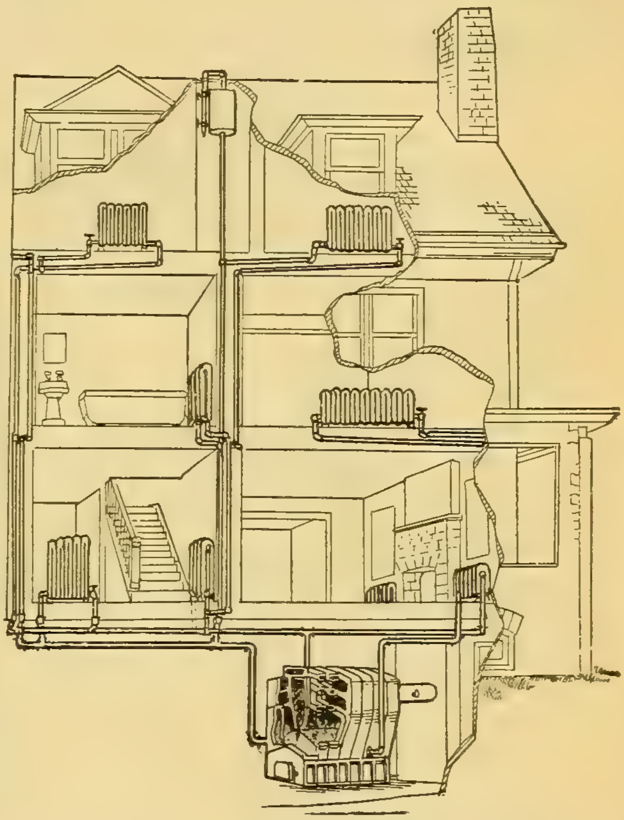
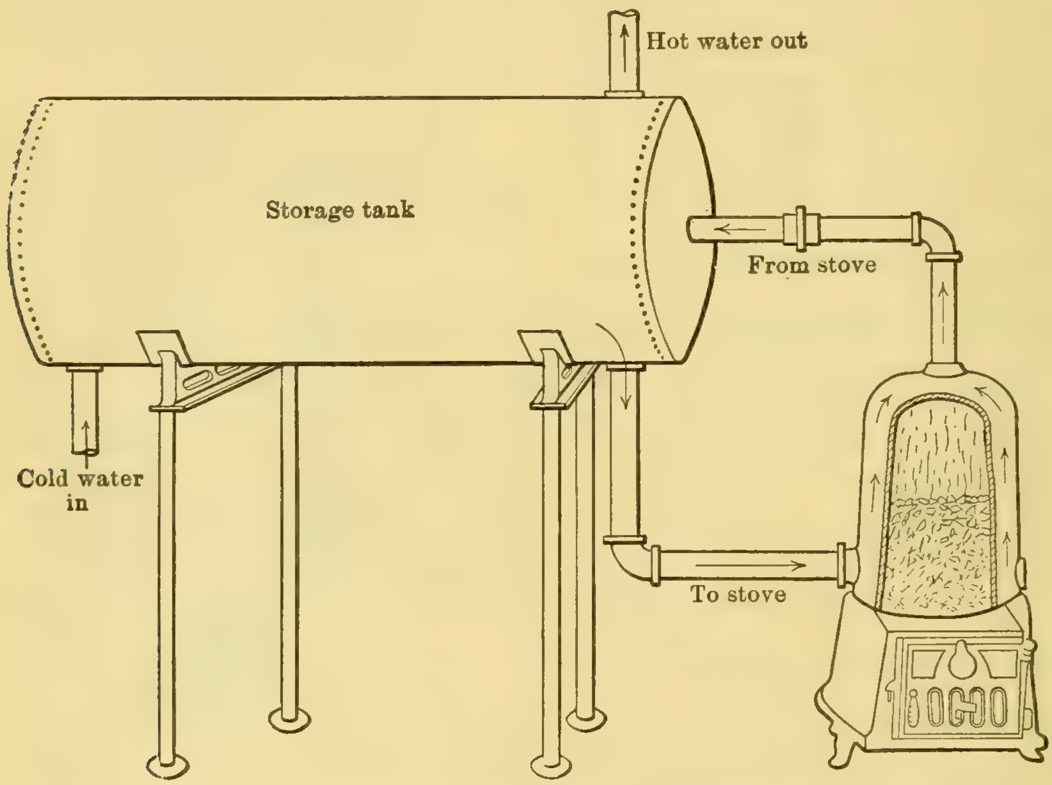


FIGURE 168. — HOT-WATER HEATING SYSTEM.

Note a single hot-water pipe from the top of the furnace and two pipes for cooled water returning to the bottom. The expansion tank is just under the roof.

Without automatic control with a thermostat, steam systems tend to overheat rooms until the fire is checked. Then when the water ceases to boil, the rooms are underheated until the fire is increased. Steam systems lack the regularity of heat delivery noticed in the hot-air and the hot-water systems.

117. Winds. — Winds are parts of huge convection currents on the earth. Too many factors enter into their formation to permit a full discussion here. In general, however, winds are set up in the earth's surface *toward* heated areas (Figure 171). The *trade winds* blow steadily toward the heated region of the equatorial calms to replace the air that rises in those regions. *Land and sea breezes* reverse daily



Courtesy Guerney Heater Mfg. Co.

FIGURE 169. — HOT-WATER SUPPLY SYSTEM.

The stove has double walls around the fire box. Convection currents through the stove and tank are shown by arrows. The pressure of the cold water supply causes the hot water to flow from the faucets.

during warm weather. They blow toward the land during the day when the land is warmer than the water. The air over the land is heated, expands, and is pushed up and horizontal currents set in toward the heated area. The reverse movement occurs at night. *Monsoons* of the Indian Ocean are seasonal winds that blow *toward* the land during the summer season, when the land is warmer than the water.

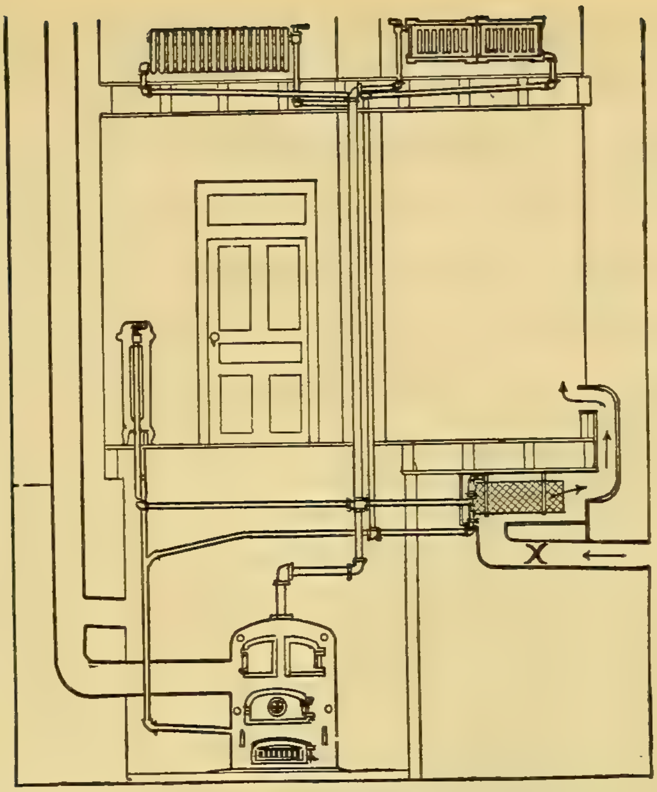


FIGURE 170.—STEAM HEATING SYSTEM.

Steam pressure keeps the radiators full. Condensed steam returns to the boiler to be vaporized again. Outdoor air is heated by a radiator under the floor for the room at the right.

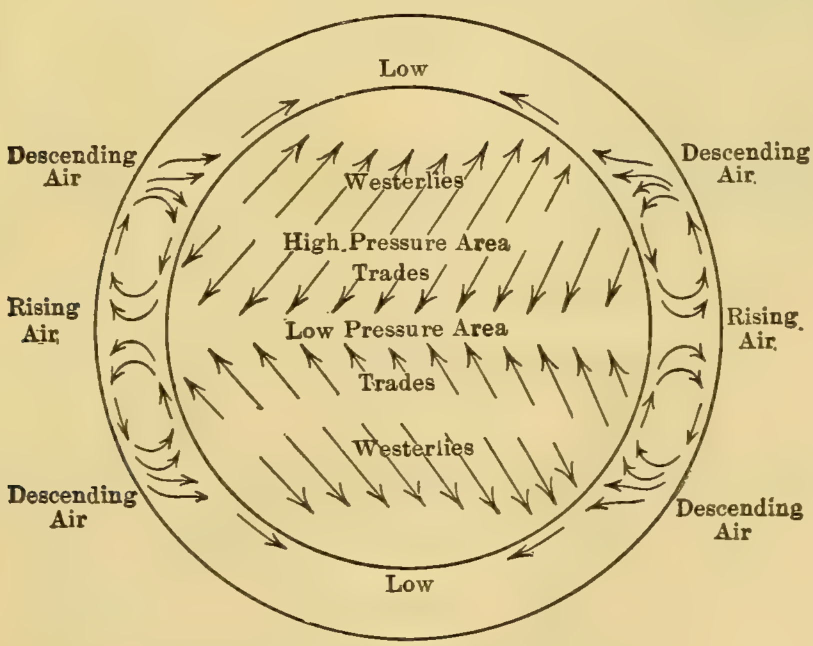


FIGURE 171.—WIND CHART.

The outer ring shows air movements in the atmosphere and the inner circle shows the direction of winds across the earth's surface.

During the winter, the air over the warmer ocean is pushed up by the reversed monsoon blowing *off* the cooler land.

118. Radiation. — The sun warms the earth and the earth loses its heat by a third method of heat transference called *radiation.* All bodies that are warmer than their surroundings tend to lose heat, and all bodies cooler than their surroundings tend to gain heat by this method. The fact that there is a third method of transmitting heat, or rather, heat-producing energy, can be demonstrated by the following experiment.

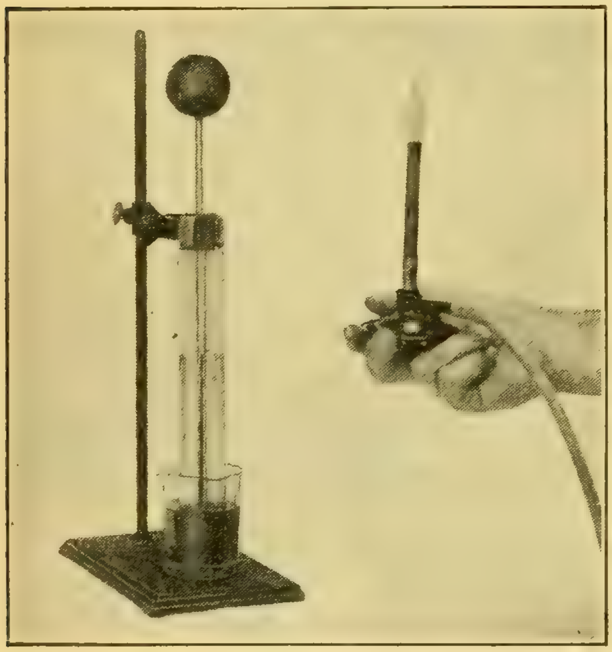


FIGURE 172. — TESTING RADIATION.

EXPERIMENT 49. — Blacken the bulb of an air thermometer by holding in the luminous bunsen flame. After the bulb is cooled and the index adjusted, hold a foot to one side of it an ordinary non-luminous bunsen flame (Figure 172). The index will remain stationary, showing that the bulb is receiving no heat from the flame. Now make the flame luminous, and the moving of the index shows that the air in the bulb is heated. *Does this heat come to the bulb by conduction? Why? By convection? Why? What method of transmission remains?*

When the flame is made luminous, carbon particles in the gas are made very hot. The electrons in the carbon atoms are therefore caused to shift their paths of motion in such a way as to set up a series of waves in ether (§ 190). Some of these waves are light waves, others are heat waves. When these waves strike the blackened bulb, their energy is absorbed by the glass and the air molecules within. That is, the air is heated by absorbing the waves of radiant energy

sent off by the vibrating particles of the carbon in the gas flame.

All bodies emit heat waves and receive waves from other bodies. The hotter the body, the more heat it loses by radiation, and the less it gains relatively. Smooth, polished surfaces are poor radiators and poor absorbers of radiant energy. Rough, dark surfaces are good radiators when hot, and good absorbers when cold.

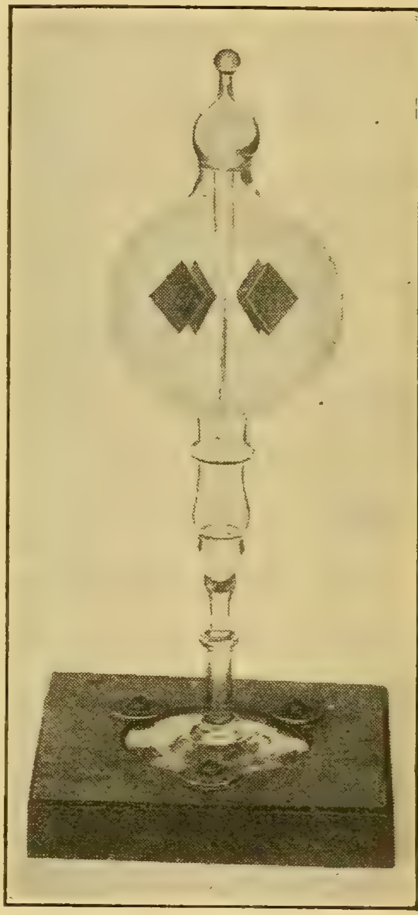


FIGURE 173. — RADIOMETER.

The temperature sense of the body is not sensitive enough to detect radiant heat from objects near the bodily temperature. We are, however, conscious of the radiant heat from the sun, so that in the summer time we seek the shade to avoid the too-powerful waves from the sun. A hot stove, an open fire, a radiator, and an electric lamp, each send out heat waves of sufficient intensity to be felt, if one approaches near enough to the source.

The air thermometer with blackened bulb is much more sensitive in detecting radiant heat and it is therefore often used to detect such transfer of heat. Another device, the radiometer (Figure 173), indicates the absorption of radiant energy by rotating when heat waves strike its vanes. These vanes are of aluminum, blackened on one side. They are pivoted in a bulb from which 99/100 of the air has been removed. Radiant energy, falling on the blackened surfaces, is absorbed, heating these surfaces more than the

polished surfaces, which reflect the waves. Air molecules rebound from the blackened sides with greater force than from the polished sides, and in doing so, exert a greater backward push against the black side. This reaction rotates the vanes and spindle. A point of interest in connection with this instrument is that the waves pass through the high vacuum of the bulb just as well as though air were present.

It should be noted that all bodies tend to become of the same temperature as their surroundings, either by absorbing the energy of heat waves, if they are colder, or by emitting more waves than they receive, if they are warmer than objects around them. Radiation is, then, a wide-spread method of heat transfer. We are, however, unconscious of most of this transfer and observe only that this body has become colder or that body has become warmer.

119. Some Results of Radiation. — The most important result of the radiation of energy by heat waves is the warming of the earth by the sun. The earth, in turn, radiates much of its heat and becomes cool during the nights and winters. If no heat were lost by the earth, it would increase slowly in temperature until it became as warm as the sun. It does increase in temperature during the long summer days when it loses by radiation less than it gains by absorption. During the winter, however, it loses by radiation the surplus gained during the summer.

Clouds and water vapor in the air prevent much of the earth's loss by radiation, and on this account the mildest days of winter are usually the cloudy ones. Frosts are often prevented in the spring or autumn by cloud blankets, which prevent heat loss by shutting off radiation from the earth just as blankets on a bed keep a person warm at night.

Fruit-growers make fires to prevent the freezing of their crop, but much of the effectiveness of the remedy lies in the smoke which spreads out and shuts off further radiation from the earth.

Heat waves from the sun are absorbed by the earth. The surface thus heated, emits waves of a greater length. The short waves from the sun pass readily through the air, through water vapor, and through glass. Glass and water vapor hinder the passage of the longer waves given off by the earth and absorb much of their energy. The glass roof of a greenhouse admits the short incoming waves, but stops the longer outgoing ones. Water vapor in the air behaves similarly, and thus maintains a higher temperature on the earth than would otherwise be the case.

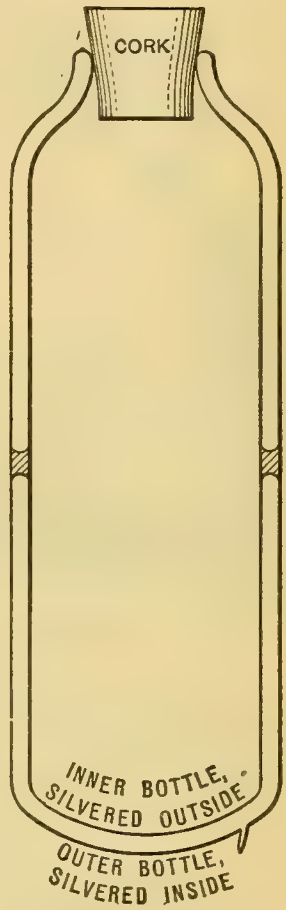


FIGURE 174. — VACUUM BOTTLE.

There is a high vacuum between the walls.

The body produces its own heat supply. We check the radiation of this heat by clothing. A house in winter requires a constant heat supply to make good the loss by radiation and conduction from the walls and windows. A good wall should be non-conducting, so that little heat can make its way through.

120. Vacuum Bottles. — The prevention of heat transmission is often desirable. The vacuum bottle, originally devised by Dewar as a container for liquefied gases, is effective in preventing rapid heat transmission either inward or outward. Because of this, hot or cold substances put into the vacuum bottles change temperature very slowly. A

double-walled bottle has its adjacent surfaces silvered (Figure 174), and the air from the space between the walls exhausted. If a hot liquid is put into the bottle, the liquid cannot lose its heat by convection because of the vacuum space; conduction is prevented by the vacuum and the insulating glass walls; and the silvered surface reflects the radiant waves back into the liquid and thus prevents loss of heat by radiation. While the bottle is not a perfect insulator, it will keep liquids hot for some hours. Cold liquids inside cannot receive heat from outside for the same reasons. A fiber-packed space replaces the vacuum in some bottles, with nearly as good results

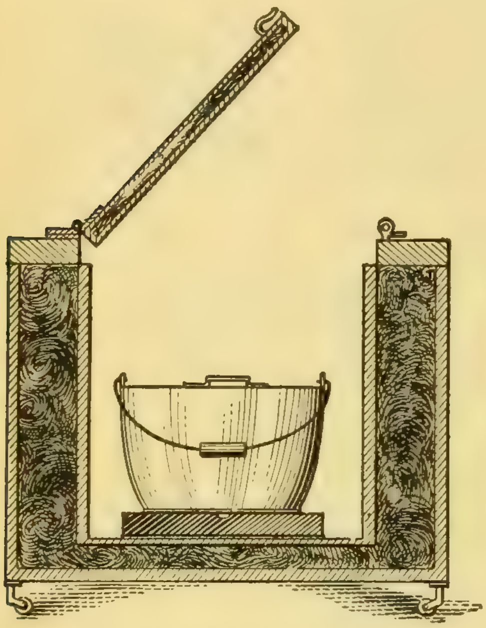


FIGURE 175.—FIRELESS COOKER.

Between the double walls loose, non-conducting material reduces conduction and prevents convection.

121. Fireless Cooker. — In a fireless cooker (Figure 175), a double-walled box with the space between packed with fibrous material, acts very much like the vacuum bottle described above. Food to be cooked is raised to the cooking temperature over a fire and then, together with hot iron or stone plates to maintain the heat supply, is put into the cooker and the cover put on tightly. While the insulation is not as good as in the vacuum bottle, the food will remain at the cooking temperature for several hours before enough heat has escaped to stop the cooking. Fuel is used only during the time required to heat the food to cooking temperature and to heat the plates. Fireless cookers are adapted to the preparation of foods requiring slow cooking.

QUESTIONS

1. In what ways is heat transmitted?

2. One end of an iron rod is thrust into a fire. What happens to the molecules at the heated end?

3. Are molecules at the other end of the rod affected? If so, how?

4. Define conduction, and give three illustrations of the conduction of heat.

5. Name five solids that conduct heat rapidly.

6. Name five solids that conduct heat so poorly that they may be called insulators.

7. Compare the conductivity of metals with that of non-metallic solids; of fluids with solids.

8. How does a solid become heated throughout when heat is applied to one portion of it?

9. Why are fibrous or granular substances good insulators?

10. How is the density of a gas affected by heat? How does this density change affect the pressure of the gas?

11. Define convection. What word may usually be associated with convection?

12. Does warm air over a fire rise, or is it pushed up? Why?

13. Give four examples of the useful convection of heat.

14. Describe in detail some house-heating device depending on convection. What other systems are used?

15. Explain in detail the origin of winds.

16. If you should set a hot body in the center of the floor of a room, and then close the room tightly, what movement of air in the room would take place and when would such movement cease?

17. Heat from a burning building often breaks windows in nearby buildings. How is such heat transferred?

18. Define radiation. Is heat or heat-producing energy transmitted by radiation?

19. Describe a method of detecting radiant energy.

20. Give three illustrations of the useful transfer of thermal energy by radiation.

SUMMARY

Heat is the energy that a substance possesses due to the vibration of the molecules of the substance.

Increasing or decreasing the molecular vibration increases or decreases the heat energy possessed by the body.

The physical state in which a body exists depends upon the amount of heat contained by the substance.

Heat may be transmitted from hot bodies to cold ones by conduction, by convection, or by radiation.

Conduction is the transfer of heat by molecular collision.

Solids differ in conductivity; metals are good conductors of heat. Liquids and gases are poor conductors. The best practical insulators are dead air spaces in fibrous material.

Conduction is the method by which heat passes through solids; it is therefore useful whenever such transmission is necessary.

Convection is the transfer of heat by moving currents of a fluid. Convection results from an unequal pressure in fluids, due to the expansion of the heated portion of the fluid. Convection is the method of heat transfer usually made use of in heating buildings. Furnaces and heaters are devices used to set up convection currents.

Radiation is the transmission of energy by ether waves. Certain radiant waves produce heat when absorbed by the substance upon which they fall. Radiation requires no material substance for its propagation. Radiation takes place equally in all directions. Radiation is the method by which the sun warms the earth. Opaque substances and some transparent ones shut off radiation.

The vacuum bottle and the fireless cooker are devices for **preventing** the transmission of heat by the three methods.

EXERCISES

1. What do you think you would notice about the molecules of any common substance if you could see them?

2. When Davy melted two pieces of ice by rubbing them together, where did the required heat originate?

3. A steel rod is wound with wire carrying an alternating current. According to the theory of magnetism, the molecules of steel are turned end for end many times per second. How is the temperature of the rod affected?

4. How is the conductivity of a metal involved when a flatiron is heated? When the iron is used?

5. Water vapor in the atmosphere prevents the loss of the earth's heat by radiation. Explain why clear days in the winter are colder than cloudy days, although we receive more heat from the sun on the clear days.

6. Why does the first layer of ice on a pond freeze more readily than the succeeding layers?

7. Mountain peaks are nearer the sun than the adjacent valleys. Why are the mountains so much colder than the valleys?

8. Why are glass roofs used on greenhouses?

9. A fire is built under a water compartment of a steam furnace and a person in a distant room is warmed. Explain in detail the transmission of heat from the fire to the person.

10. By what method of transmission does heat pass through a vacuum? How is this method of transmission prevented in a "thermos" (vacuum) bottle?

11. How are campers around an open fire warmed? What are the disadvantages of this method?

12. Should a steam radiator be polished or left rough? Why? Does this reason apply to a coffee pot?

13. Snow under a dead leaf melts much faster than snow beside it. Explain.

14. Why does a thermometer with a long, thin bulb register more promptly than one with a spherical bulb?

15. A moistened finger will freeze to iron having a temperature much below freezing, but the finger does not freeze to wood that is as cold as the iron. Explain.

16. A wooden tub separates the freezing mixture in an ice cream freezer from the air, but a metal can separates the freezing mixture from the substance to be frozen. Explain this choice of material.

17. Wooden handles are often used on cooking utensils and on soldering irons. Explain this usage.

18. What property makes aluminum valuable for a cooking utensil? Why are iron handles used on aluminum utensils?

19. What materials are used for covering steam pipes?

20. Show how you would construct the wall of a refrigerator. Show how heat from the food is conveyed to the ice.

21. Explain why ice is placed near the top of a refrigerator.

22. What kind of fabric makes the warmest clothing? Why does clothing keep the body warm?

CHAPTER XI

CHANGE OF STATE

122. Change of State. — The freedom of movement of the molecules of a substance determines whether it is a solid, a liquid, or a gas. To cause molecules to move more freely, energy must be given to them. When molecular motion slows down, the molecules must lose energy which appears in some other form. Every change in state of a substance means a change in the activity of its molecules. In every such change, energy must be either absorbed or liberated. Heat is the form of energy taken in or given off during changes of state.

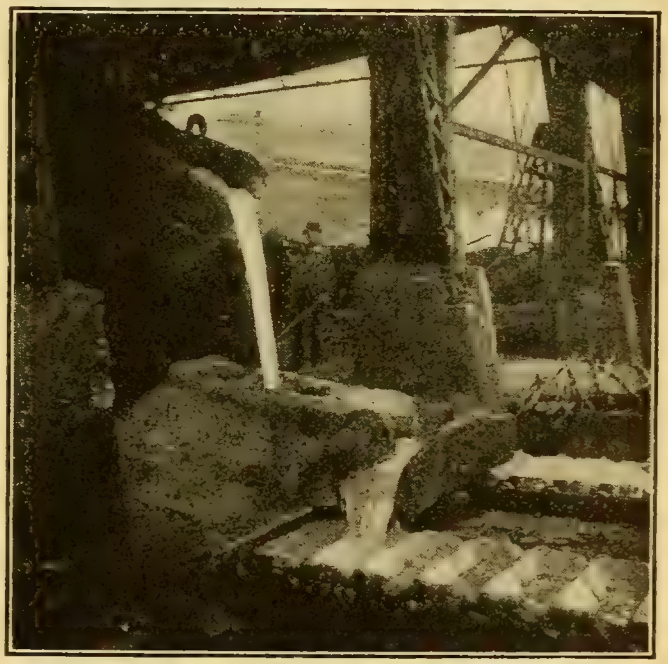


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FIGURE 176. — MELTED PIG IRON POURING INTO MOLDS.

Solidification, or freezing, is the change from the liquid to the solid state. The reverse change, solid to liquid, is melting or *fusion.*

The change from a liquid to a gas is evaporation or *vaporization.* The change of a gas to a liquid is *condensation.*

123. Fusion and the Melting Point. — A block of ice melts slowly in warm air. Butter softens on the table on a

hot day, and quickly changes to a liquid when put into a hot dish. The bar of solder runs to a liquid when touched by the hot soldering iron. In all these cases, the molecules of the solid gain greater activity as they absorb heat, until finally they can slide freely over one another (Figure 176). Then the substance is in its liquid state.

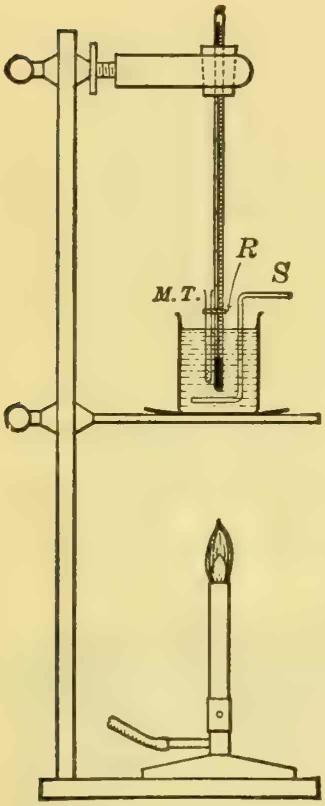

FIGURE 177. — A thin melting tube (MT) holds the substance to be tested. The thermometer gives the melting point.

When a crystalline substance begins to melt, its temperature remains constant until the change of state is complete. The amount of heat required to effect such a change varies with different substances, but is a definite amount for the unit quantity of any particular substance.

The heat of fusion is the heat required to melt a gram of a solid substance to a liquid without changing its temperature. A *calorie* is the quantity of heat required to raise 1 gram of water 1° C. To melt 1 gram of ice requires 80 calories.

Crystalline substances have well-marked melting points, which often aid in the identification of the solid (Figure 177). *Amorphous* (non-crystalline) solids soften throughout the mass in such a way that the melting point cannot be determined within several degrees. Among such amorphous solids of indefinite melting point are fats, waxes, glue, tar, and glass. The melting points of some common substances are given in the table on the next page.

The melting point of ice is used to locate one of the fixed points of the mercury thermometer. As the ice melts, it

cools the substances in the refrigerator by absorbing heat from them.

MELTING POINTS IN DEGREES CENTIGRADE

Mercury . .	−39.5°	Camphor . .	176.4°	Gold	1062°
Ice	0°	Tin	232°	Copper . . .	1083°
Nitroglycerine .	4°	Lead . . .	327°	Cast iron (approx.) .	1200°
Alum	84.5°	Aluminum .	657°		
Sulphur . .	114.5°	Silver . . .	961°	Platinum .	1753°

Since ice is common and its melting point is below the temperature at which decomposition of foods takes place, ice is the most practical substance for refrigeration.

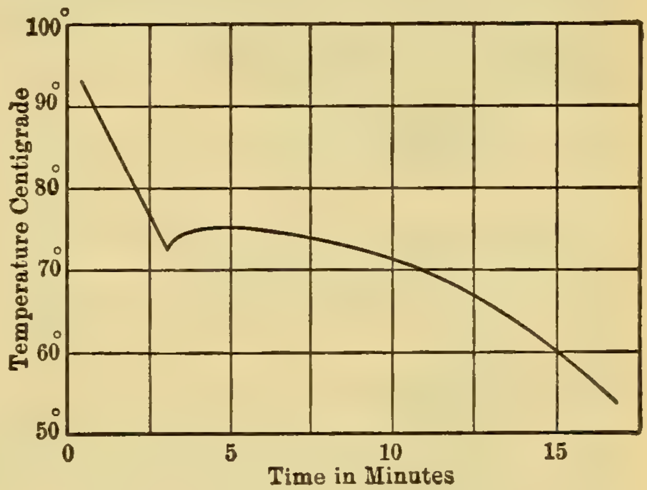

FIGURE 178. — COOLING CURVE OF ACETAMID.

The straight line shows cooling of liquid. From the 3d to the 7th minute the heat of solidification kept the temperature from falling.

124. Freezing. — In changing a liquid to a solid, the molecules of the substance become less active and the heat that was absorbed on melting is liberated. This can be shown by melting a crystalline solid, and observing the temperature as it cools again and solidifies (Figure 178). On cold winter nights, pails of water are sometimes placed in a vegetable cellar so that the heat given off by the water as it solidifies will keep the vegetables from freezing. The heat given off by the freezing over of large bodies of water warms the adjacent shores a little.

The melting point and the freezing point of a substance are identical. Both may be defined as the temperature at which both the solid state and the liquid state of a substance

may exist side by side. A cake of ice floating in a tub of water at 0° C would remain unchanged in size indefinitely if we could keep the temperature and other modifying conditions constant (Figure 179).

125. Effect of Dissolved Substances on the Freezing Point. — When salt is added to water, the solution freezes

FIGURE 179. — ICEBERG LAKE, GLACIER NATIONAL PARK. Even in midsummer, the water is nearly ice cold.

below 0° C. The more salt dissolved, the greater the depression of the freezing point. Thus a 10% solution of salt freezes at −7.35° C, and a 20% solution at −12.96° C. A saturated solution of common salt freezes at −21° C. Other soluble substances have the power of depressing the freezing point of water. Apparatus for testing freezing points is shown in Figure 180. For dilute solutions this statement can be made: *The depression of the freezing point of a solvent is proportional to the amount of the dissolved substance.*

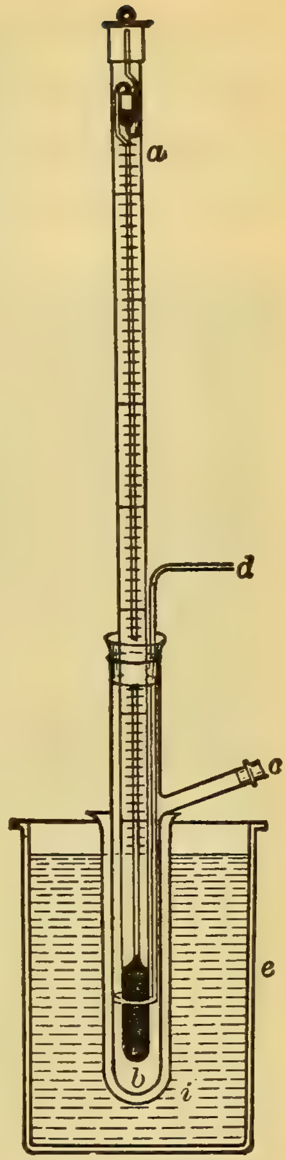

FIGURE 180. — This delicate thermometer (*a*) indicates $\frac{1}{1000}$ of a degree change in temperature. The liquid to be tested is placed in the tube (*b*) and chilled by a freezing mixture (*i*) in the outer jar; (*d*) is a stirring rod.

Alcohol is added to the water in automobile radiators so as to depress the freezing point of water and obtain a non-freezing liquid for cold weather. A good non-freezing mixture for temperatures not below 5° F consists of 15% alcohol, 15% glycerine, and 70% water by volume. For temperatures not below 15% F, equal parts by volume of alcohol and glycerine make up one third of the solution, and water the other two thirds. Although glycerine is slightly injurious to rubber, it helps to make a very desirable anti-freezing liquid.

EXPERIMENT 50. — Fill a funnel with finely crushed ice and another with a mixture of equal parts of ice and rock salt. Support the funnels on ring stands, so that the stem of each will extend into a graduate. Insert a thermometer in each funnel (Figure 181). After five minutes read the thermometers and the amount of liquid in each graduate. *What effect has the salt had upon the melting point of ice? Upon the rate of melting?*

126. Freezing Mixtures. — The salt and ice in an ice cream freezer give another example of the effect of a dissolved substance (salt) on the freezing point of a solvent (water). When salt comes in contact with ice, some of the salt dissolves in the thin film of water that immediately forms on the ice (Figure 182.) Heat is required to dissolve the salt (§ 129), and is absorbed from the surroundings. As more ice melts and more salt dissolves, additional heat is needed and the solution

cools as it furnishes this heat. The cooling of the solution can continue only as long as the salt dissolves. This limit is the saturated solution of salt, and the temperature of $-21°$ C is the lowest temperature that the freezing mixture of ice and common salt can give. In the freezer, the cream in the can is frozen, since heat is taken from it to melt the ice and dissolve the salt.

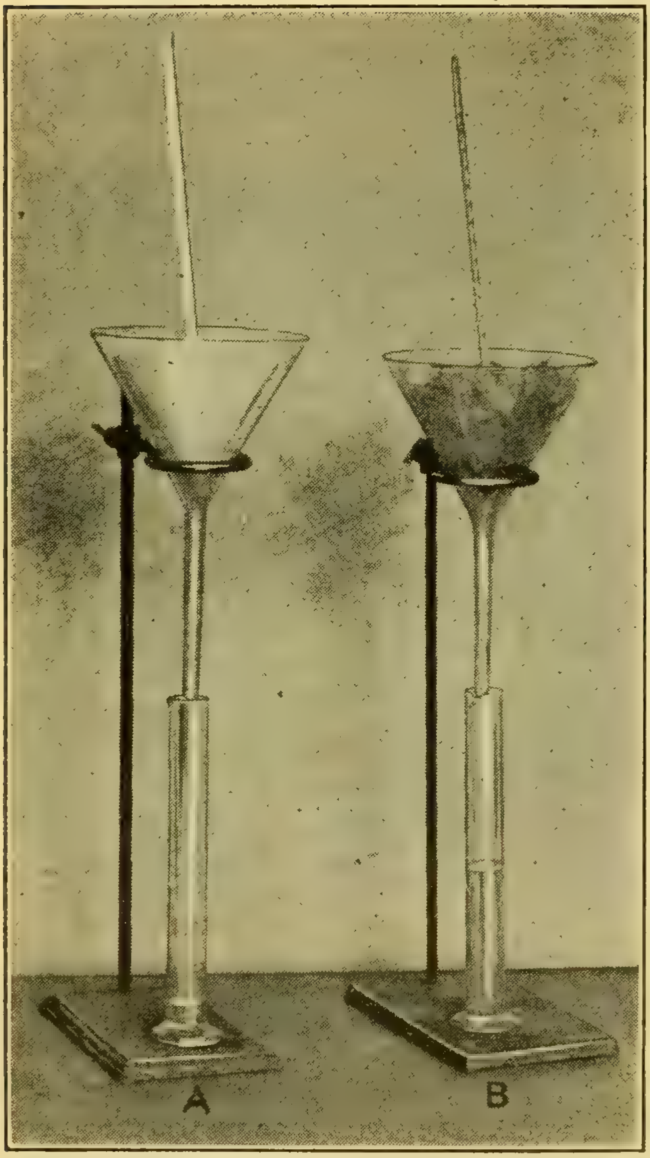

FIGURE 181. — *A*, contains pure ice; *B*, ice and salt.

Ammonium chloride, potassium nitrate, and crystallized calcium chloride are other salts that make good freezing mixtures with ice or snow. The finer the ice and salt and the more thoroughly the two are mixed, the quicker will be the cooling by the freezing mixture. A mixture of 7 parts snow and 3 parts crystallized calcium chloride ($CaCl_2 \cdot 6\,H_2O$) will give a temperature of nearly $-54°$ C.

127. Effect of Pressure on Freezing Point. — Increased pressure raises the melting point of substances that, like wax, contract on solidifying ("freezing") and lowers the melting point of substances like water that expand on freezing. The latter case is of the greater practical interest.

FIGURE 182. — SALT MELTING ICE.

Note the places where the smooth ice was melted by salt scattered on it.

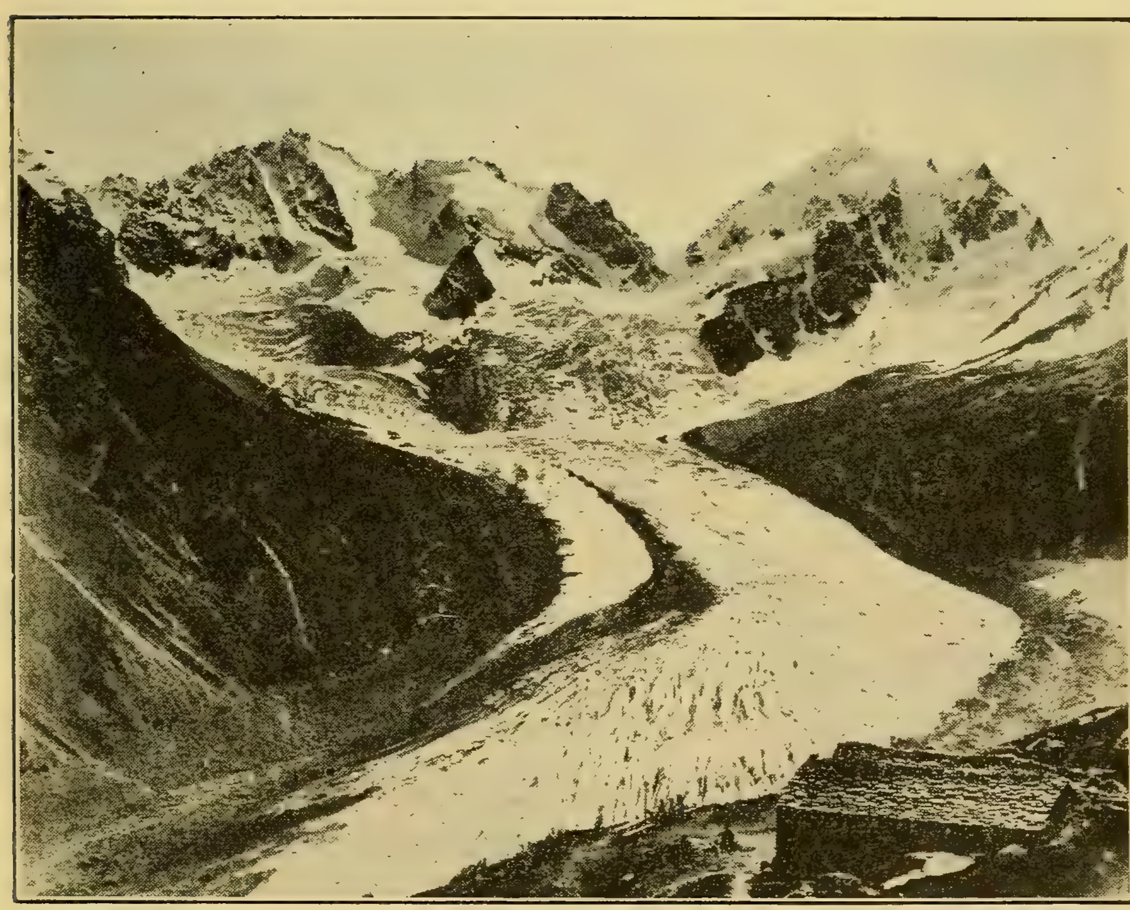

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FIGURE 183. — A GLACIER IN THE SWISS ALPS.

The melting of the ice under pressure enables it to follow the depressions.

When two blocks of ice are pressed together, the temperature of the two ice surfaces in contact is above the new melting point due to the increased pressure. Hence a thin layer of ice has to melt, since its temperature is a degree or so above the melting point. When the pressure is relieved, however, the water from the melting immediately freezes again and unites the two cakes of ice. Similarly, a snowball may be changed into an icy mass by the pressure of the hand, and snow upon highways becomes packed by the pressure and the release of pressure due to the travel upon the roads. The movement of glaciers (Figure 183) results in part from the lowering of the melting point of ice by pressure, and the melting that follows.

While skating, the weight of the body lowers the melting point of the ice under the skate. A groove is thus melted, which prevents a sidewise slip. In this case, as in the others mentioned, the initial temperature of the snow or ice must not be too low for melting to occur. Thus in parts of Siberia, with winter temperatures averaging $-60°$ F, it is said that the ice is too cold to be skated upon.

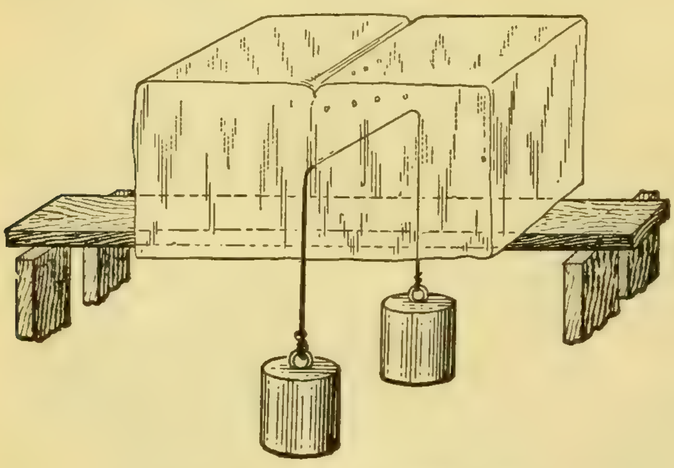

FIGURE 184. — REGELATION.

A cake of ice may be cut through by a loop of iron wire with weights attached to its ends (Figure 184). The pressure causes the ice to melt on the under side of the wire, but the water formed flows above the wire and freezes once more. In this manner the wire slowly cuts its way downward through the ice, leaving a solid block above.

This process of melting ice due to increased pressure, and the subsequent refreezing of the water as it flows out of the region of increased pressure, is known as *regelation*.

In general, it may be said that any change in state which produces a bigger bulk or volume is made difficult by an increase in pressure. The raising of the boiling point of water with pressure and the lowering of its freezing point by the same cause illustrate this principle.

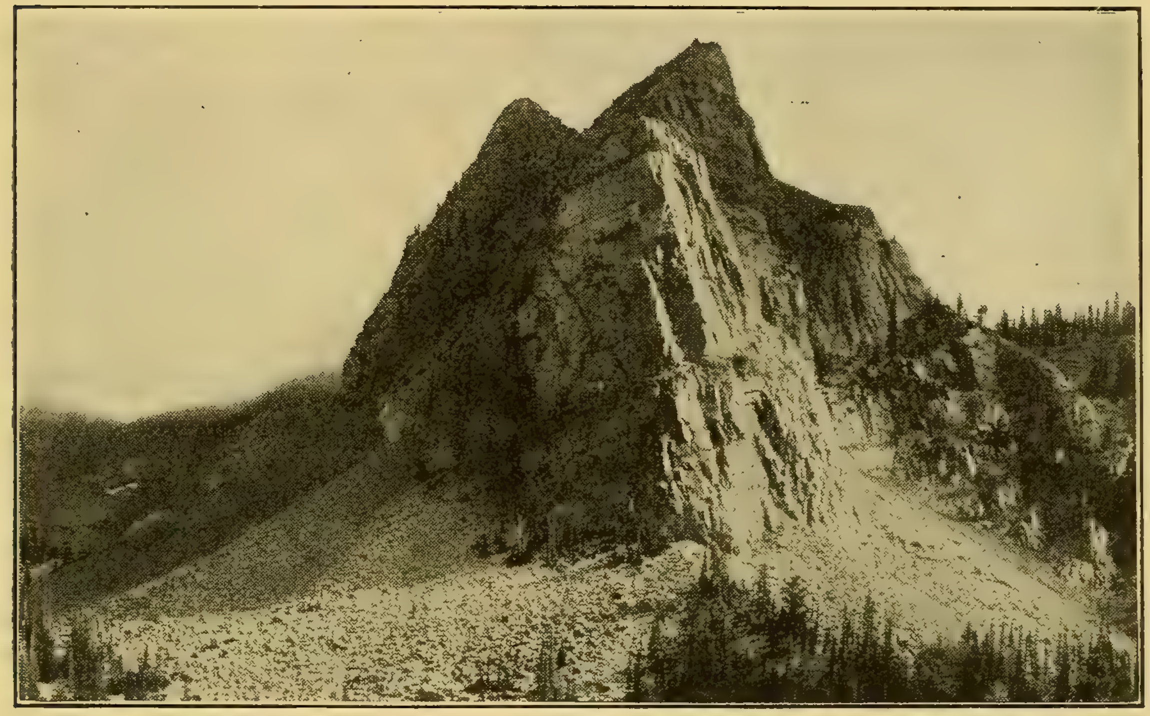

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FIGURE 185. — A UTAH MOUNTAIN.

Tons of rock have been broken from the face of this bold peak by the force of water freezing in the cracks.

128. Volume Change in Solidification. — Some substances, like paraffin, contract when they solidify and the solid sinks in the liquid since it is heavier, volume for volume. Other substances, like water, expand on freezing. To this behavior of water is due the bursting of water pipes in winter and the disintegration of rocks (Figure 185) from water freezing in their crevices. Type metal takes a sharp impression of the

mold, since it expands in passing from the liquid to the solid state.

129. Solution and Temperature. — When a solid dissolves in a liquid, the change that occurs is similar to the change in state of a solid to a liquid. The attraction that holds together the molecules of the dissolved solid is broken, and the separated molecules are drawn in among the molecules of the solvent. With these changes in molecular attraction and in the movement of the molecules, it is not strange to find that the solution of a solid in water produces heat effects.

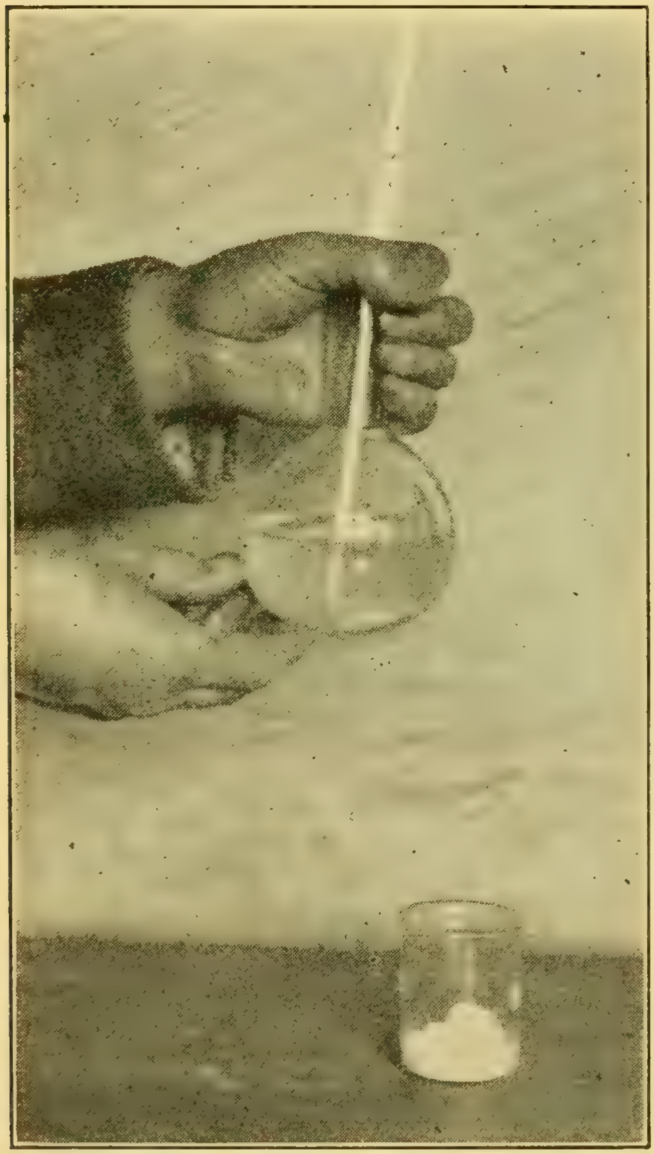

FIGURE 186. — COOLING BY SOLUTION.

EXPERIMENT 51. — Cover the bottom of a flask with "hypo" to the height of an inch. Half fill the flask with water at room temperature (Figure 186). Take the temperature immediately. Remove the thermometer and, holding the flask by the neck, shake it with a rotary motion until the hypo no longer appears to dissolve. Touch the bottom of the flask, and confirm your observation by again taking the temperature with the thermometer. *Is heat absorbed or given out during solution?*

Heat is absorbed in dissolving most substances in water. In the solution of other substances, such as caustic soda, heat is liberated. Many are familiar with the great heat pro-

duced when a can of lye is dissolved in water before being poured down the waste pipe of a kitchen sink. In this case, the giving of heat is probably due to some chemical reaction between the dissolved substance and the solute.

QUESTIONS

1. What determines whether a substance exists as a solid, a liquid, or a gas?

2. What energy changes occur during change of state?

3. What happens to the molecules of a substance when it melts?

4. Define *heat of fusion.* Explain the meaning of the phrase "without change of temperature" in the definition.

5. How does the melting of amorphous substances differ from that of crystalline substances?

6. For what purposes is the knowledge of melting points valuable?

7. Define *solidification* or *freezing.*

8. Account for the heat given off by a substance when it freezes.

9. State the relation between the depression of the freezing point of a solvent and the amount of the dissolved substance. Give an example.

10. Why is alcohol added to the water in the radiator of an automobile in the winter time?

11. Explain how the low temperature is obtained with a freezing mixture of ice and salt.

12. What effect has increased pressure on the melting points of solids?

13. Explain how two blocks of ice are made into one by pressing them together.

14. What is *regelation?*

15. What kinds of change of state are made more difficult by an increase in pressure?

16. Name one substance that contracts on solidifying; two that expand.

17. Why should a heat change be expected when a solid is dissolved in water?

18. What heat change occurs when most solids are dissolved in water?

130. Evaporation. — Dew disappears from the grass, clothes dry on the line, and drenched pavements become dry. These are but a few familiar examples of evaporation, a natural process interwoven everywhere in the weather, the climate, and in the fertility of the soil, and in our own bodily comfort. We cannot see how water silently evaporates from a surface, but have to imagine how the process goes on. We picture some of the molecules, which have more energy than the rest (Figure 187) flying off in spite of the molecular attraction of the liquid. The molecules that remain behind have less energy; hence the liquid is cooled by the evaporation.

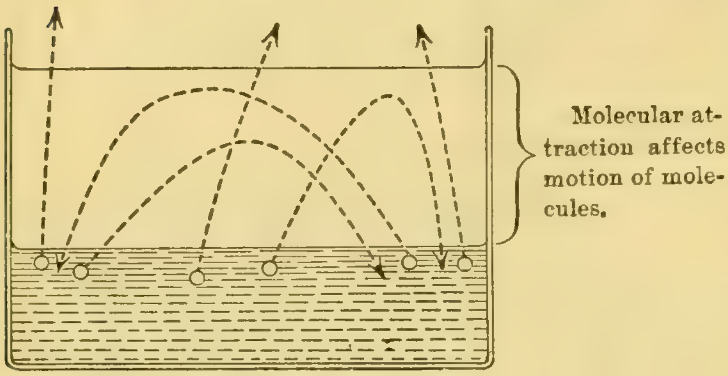

FIGURE 187. — Three molecules are shown escaping and three others attracted back again by the liquid. The very short distance through which this attraction can act has been greatly exaggerated.

After a time some of the molecules which have flown off return to the surface and again become part of the liquid. If the water is confined, as in a partly filled and stoppered bottle, the number of molecules returning to the liquid after a time equals the number of molecules leaving it (Figure 188). Then the vapor is said to be in equilibrium with its liquid; that is, the pressure of the water

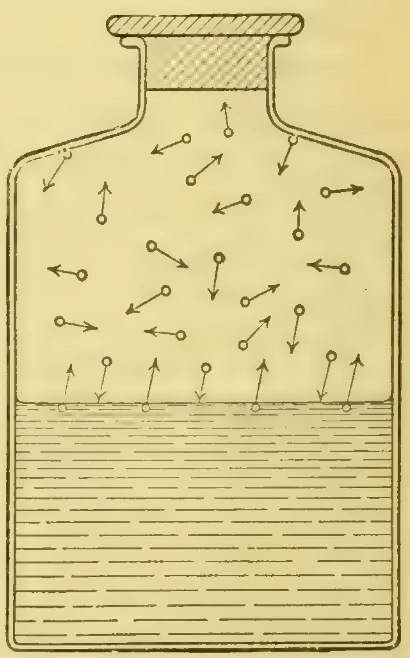

FIGURE 188. — MOLECULES IN A SATURATED VAPOR.

As many reënter the liquid as leave.

vapor is equal to the vapor pressure of the liquid (its tendency to change to vapor). Usually we say, however, that the air above the water surface is *saturated* with water vapor. Effective evaporation is then at an end. If the water is in an open dish, the vapor pressure of the liquid enables the evaporation to go on under ordinary conditions until the water disappears.

The pressure of water vapor (as of any vapor) increases with the temperature, as shown in the following table:

PRESSURE OF WATER VAPOR

(In millimeters of mercury)

0.0° C	4.6 mm	25°	23.5 mm	70°	233.8 mm
5.	6.5	30	31.6	80	355.4
10.	9.2	40	54.9	90	526.0
15.	12.7	50	92.1	100	760.0
20.	17.4	60	149.2	120	1480.0

At 100° C, the pressure of water vapor is 760 mm, which is the normal atmospheric pressure. This is the condition of equilibrium when water is at its boiling point, 100° C. Pressure of water vapor is also known by the older names of *tension of water vapor* and *aqueous tension.*

An evaporating liquid absorbs heat from objects around it and the objects become colder. The skin is cooled as water evaporates from the wet hand, and the hot ground is rapidly cooled when water from a summer shower is turned into vapor again. That heat is required for evaporation may readily be shown by experiment.

EXPERIMENT 52. — Wrap a wet piece of cheese cloth around the bulb of a thermometer (Figure 189). *What happens to the mercury column? Where does the water get heat for its evaporation?* The thermometer with uncovered bulb gives a standard for comparison.

Repeat the experiment, using a cloth dipped in ether. *Account for the fall of the mercury column.*

FIGURE 189.

The water and the ether were at room temperature when allowed to evaporate. The vapor formed was no warmer than the evaporating liquid. Hence the heat absorbed from the thermometer was simply used in changing a substance from the liquid to the gaseous state. Heat that does this is *heat of vaporization.*

The heat of vaporization of a substance is the heat required to change 1 gram of the substance from a liquid to a vapor.

131. Conditions Favorable to Evaporation. — The rate of evaporation of a liquid is favored by four conditions. The first is an *increase in temperature.* The higher degree of heat increases the average velocity of the molecules and more leave the evaporating surface within a given time. This is the case when clothes are hung near the fire to dry, or are exposed to the direct heat of the sun. Secondly, an *increase in the area of the evaporating surface* hastens evaporation, since this brings more of the molecules near the surface so that they can break away. This is the reason for evaporating brine in wide shallow

FIGURE 190. — DRYING CLOTHES ON A WINDY DAY.

basins or tanks to obtain the salt (Figure 191).

A *decrease in the number of molecules of the vapor over the evaporating surface* is the third favoring factor. The fewer the molecules above the liquid, the less chance will there be for the escaping molecules to return to the liquid. If the space above the liquid is saturated with vapor, as many molecules return to the liquid as leave its surface. Hence there is no effective evaporation. Winds or air currents are the usual means for taking away the molecules of vapor from over a liquid. A practical application of this is the rapid drying of clothes on a windy day (Figure 190). Also chemical manufacturers blow air through their hot evaporating solutions. The fourth factor in rapid evaporation is *a decrease in pressure over the evaporating sur-*

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FIGURE 191. — USING THE SUN'S HEAT TO OBTAIN SALT BY EVAPORATION OF SEA WATER IN SHALLOW BASINS.

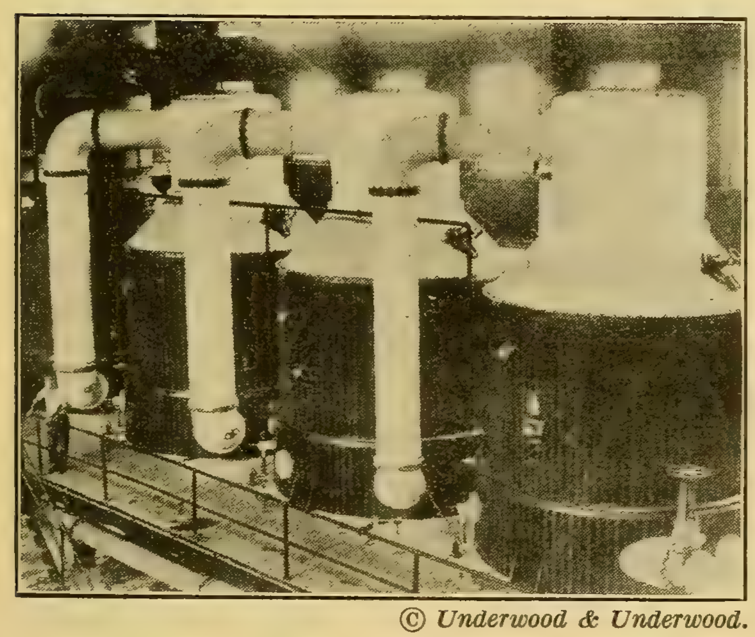

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FIGURE 192. — Vacuum pans are used in boiling down sugar solutions during the process of refining crude sugar.

face. This results in fewer gas molecules in a given space and a better chance for the escape of molecules from the liquid surface, since less energy is needed to start the surface molecules on their journey. For this reason, sugar solutions and glycerine are evaporated in refineries under diminished pressure (Figure 192), so that a harmful degree of heat will not need to be used. In most cases of rapid evaporation, several of the factors favorable to evaporation are present.

132. Phenomena of Boiling. — Evaporation and boiling are alike in that both change a liquid to a vapor and both take place against the pressure of the atmosphere. The differences between them become plain when we observe what occurs in boiling.

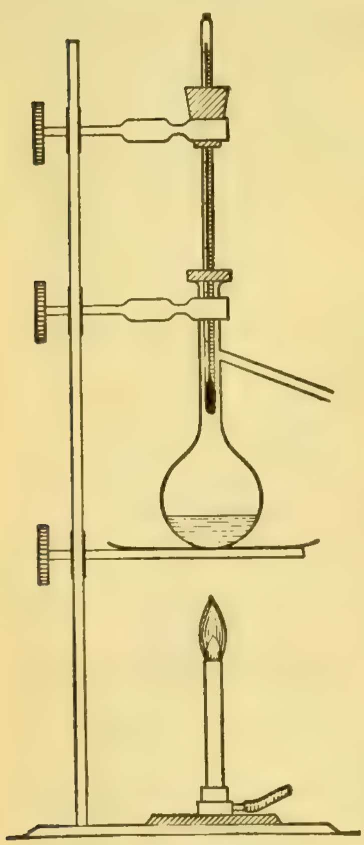


FIGURE 193.

EXPERIMENT 53. — Heat water in the apparatus shown in Figure 193. Note the bubbles of dissolved air that escape from the water soon after the heating begins. After a time, note where bubbles form and what happens to them as they proceed to the surface. Then take the temperature of the *top layer* of water and of the water near the bottom of the flask. *Account for the disappearance of the steam bubbles on their way up.*

Watch the formation and the action of the bubbles as the heating continues. When steam is freely escaping from the flask, take the temperature of (1) the water near the bottom of the flask, (2) the top layer, and (3) the steam. *At what temperature must water be in order to boil? Compare the temperature of the boiling water with that of the steam. What work is done by the heat applied to the boiling water?*

What happens to the steam in the delivery tube? This is condensation. *What change of state takes place in the boiling of a liquid? In the condensation of a vapor?*

When the bottom of a vessel containing water is heated, the lower layers of water are heated first and the first bubbles of steam are formed near the bottom of the flask. These bubbles as they rise through the cooler water condense and disappear. As the overlying layers of water become warmer by this condensation, the rising bubbles go higher without condensing. Finally, some of them reach the surface and break. Thereafter, the bubbles of steam form not only on the bottom and the sides of the heated vessel, but within the liquid itself. Then there is a rapid procession of bubbles to the surface and the liquid is violently agitated. The water is then boiling and its temperature is 100° C throughout.

133. Boiling Point.—The pressure of the air, the cooling effect of the air, and the cooling effect of the walls of the vessel hinder the escape of vapor from a liquid surface. The earlier molecules are cooled before they leave the flask and return to the liquid as water. As the energy of the molecules is increased by the addition of heat, the escaping molecules exert a pressure equal to that of the air on the liquid. When this condition of equal pressures is reached, the water is at *its boiling point*. *Boiling* is the evaporation of a liquid where the vapor of the liquid exerts a pressure equal to the atmospheric pressure on the liquid.

When the water is boiling, the steam and the water throughout the flask have practically the same temperature, 100°. While boiling continues, no matter how fast heat is applied, this temperature remains unchanged. The heat applied simply changes the boiling liquid to vapor faster, without making either the boiling water or the steam hotter than 100°.

A liquid having its boiling point near the ordinary tem-

perature needs but little heat to make its vapor pressure equal to atmospheric pressure. Hence such liquids, ether for example, have to be stored in tightly stoppered bottles or in sealed containers.

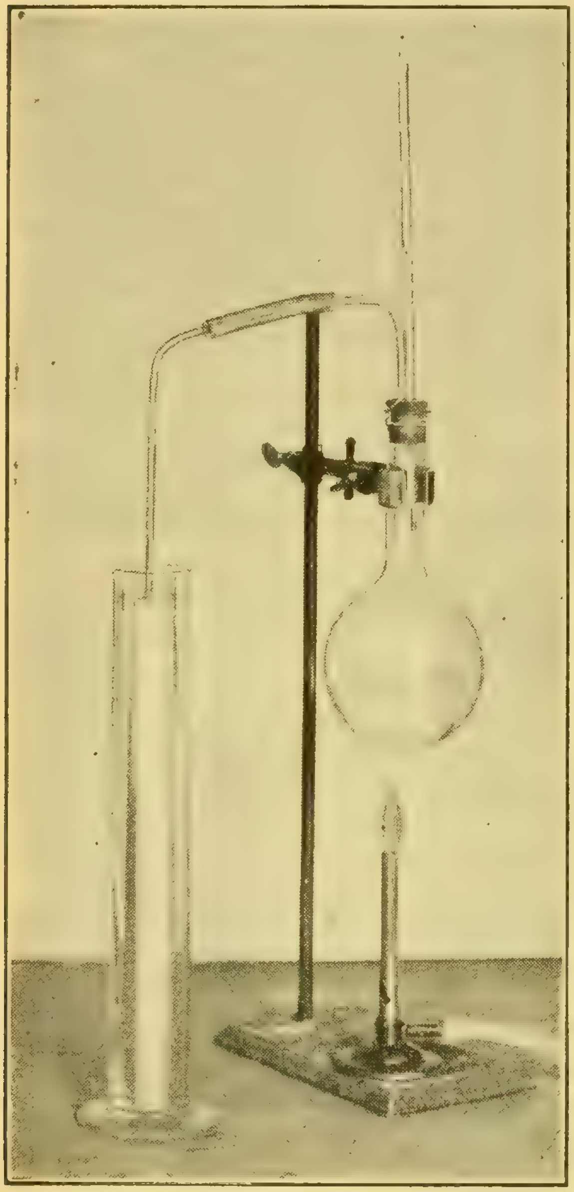


FIGURE 194. — The steam cannot escape until it has overcome the water pressure at the bottom of the tube as well as the atmospheric pressure.

BOILING POINTS OF SOME IMPORTANT LIQUIDS IN DEGREES CENTIGRADE

Ether	35°
Carbon disulphide	46°
Chloroform	62°
Methyl (wood) alcohol	66°
Ethyl (grain) alcohol	78°
Benzene	80°
Water	100°
Glycerine	290°
Mercury	357°

134. Effect of Pressure on the Boiling Point. — When it is said that water boils at 100° C, an atmospheric pressure of 760 mm is understood. The following experiment shows how increasing the pressure affects the boiling point of water.

EXPERIMENT 54. — Arrange the apparatus as shown in Figure 194 and then remove the cylinder of water. Heat the boiler until steam issues freely from the glass delivery tube. Read the thermometer. *At what pressure is this the boiling point of water?*

Replace the delivery tube in the cylinder of water and continue the heating until bubbles of steam issue from the end of the delivery tube.

Read the thermometer for the boiling point of water. *Is it higher or lower than the boiling point at atmospheric pressure? What total pressure*

did the vapor pressure of water have to equal before the water could boil? How is the boiling point of water affected by an increase of pressure?

Water boils at 100° C when the atmospheric pressure is 760 mm. When the air pressure is greater than this, more heat has to be given to the water to make its vapor pressure equal to atmospheric pressure and the boiling point of water rises above 100°. In a high-pressure steam boiler, increased pressure is obtained by confining the steam until a certain pressure is reached. Thus, when the pressure gage reads 100 pounds, the temperature of the boiling water (and of the steam) is 170° C. A pressure cooker (Figure 195) is a device for obtaining boiling water hotter than 100°, so as to get more rapid and thorough cooking.

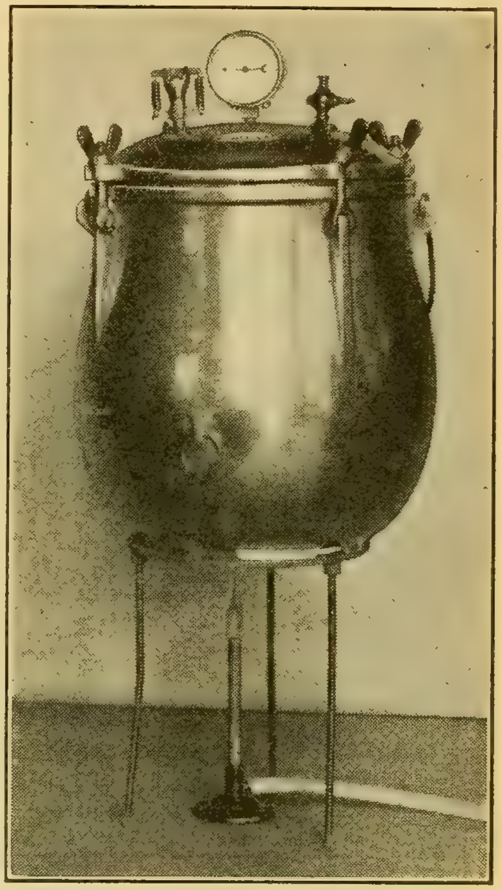


FIGURE 195. — A PRESSURE COOKER.

The lid is clamped down and the steam can escape only by raising the safety valve at the left. The gage indicates pressure.

EFFECT OF PRESSURE ON THE BOILING POINT

PRESSURE $\frac{lbs}{in^2}$	TEMPERATURE ° C	PRESSURE $\frac{lbs}{in^2}$	TEMPERATURE ° C
4.51	70	79.04	155
10.16	90	101.98	165
14.70	**100**	129.9	175
24.55	115	145.9	180
52.56	140	163.4	185

NOTE. To get the reading which would be shown on the pressure gage of a boiler, subtract 14.70 lbs from the pressures given.

The following experiment shows the effect of a decrease of pressure on the boiling point of water.

EXPERIMENT 55. — Arrange the apparatus as in Figure 196, but have the Y-tube open. Heat the flask until the water boils. *At what pressure is the water boiling?* Read the thermometer for the boiling point, and then remove the burner from beneath the flask.

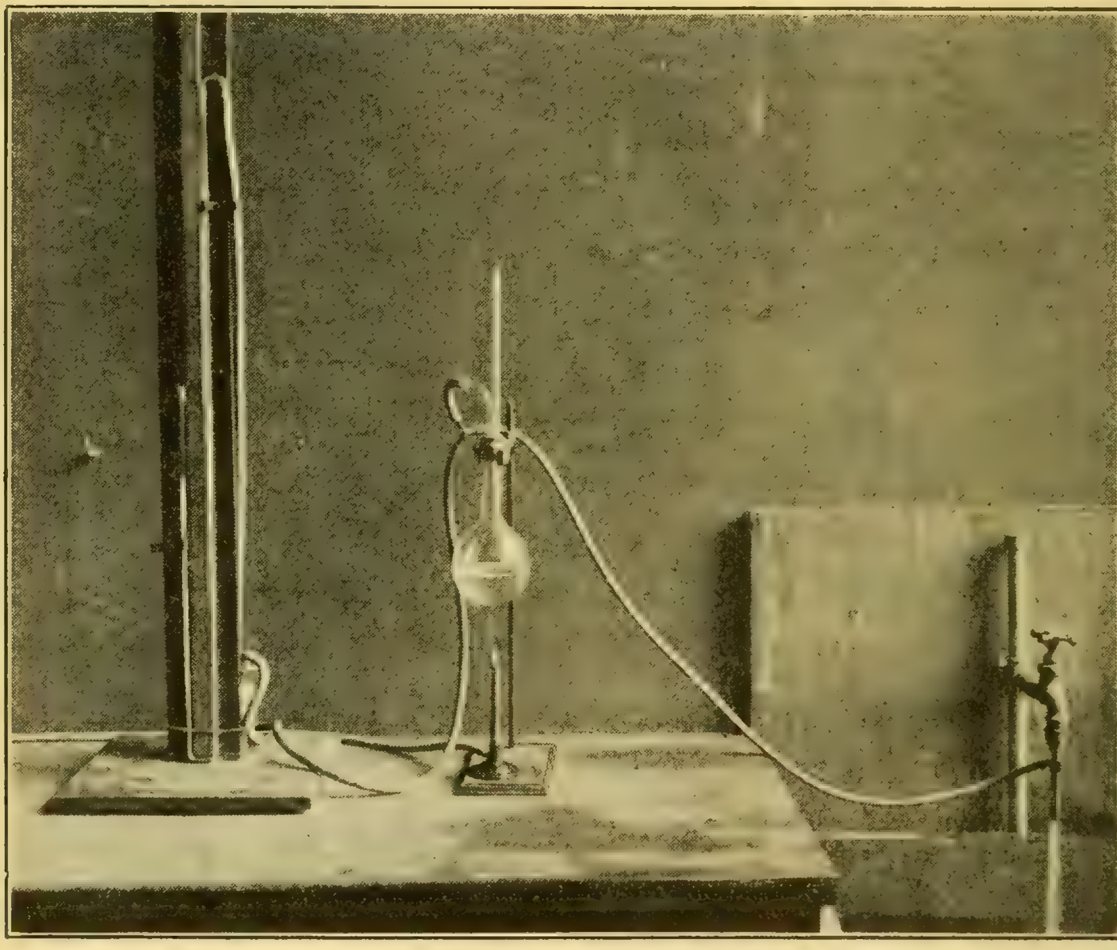


FIGURE 196. — The aspirator attached to the faucet reduces the pressure and carries off the condensed steam. The open U-tube at the left shows that the pressure is less than the atmosphere.

Attach a water aspirator to the Y-tube and slowly exhaust the flask. When the water boils, read the thermometer for the boiling point. *How does the manometer or pressure gage indicate that the pressure inside the flask is less than the atmospheric pressure? How does a decrease of pressure affect the boiling point of water?*

At pressures below 760 mm, water boils at less than 100° C. As we ascend mountains, the atmospheric pressure

decreases (§ 66) and water boils at a lower temperature. There is a change of about 1° for every 1000 feet of ascent. Thus at Denver, Colorado, which has an elevation of 5000 feet, water boils at 95° C on a clear day. Although water boils at a lower temperature, it takes longer to cook vegetables there than at sea level.

A change in pressure of 1 cm means a difference of 0.37° C in the boiling point of water at 100°. The altitude may be determined by knowing this variation in the boiling point.

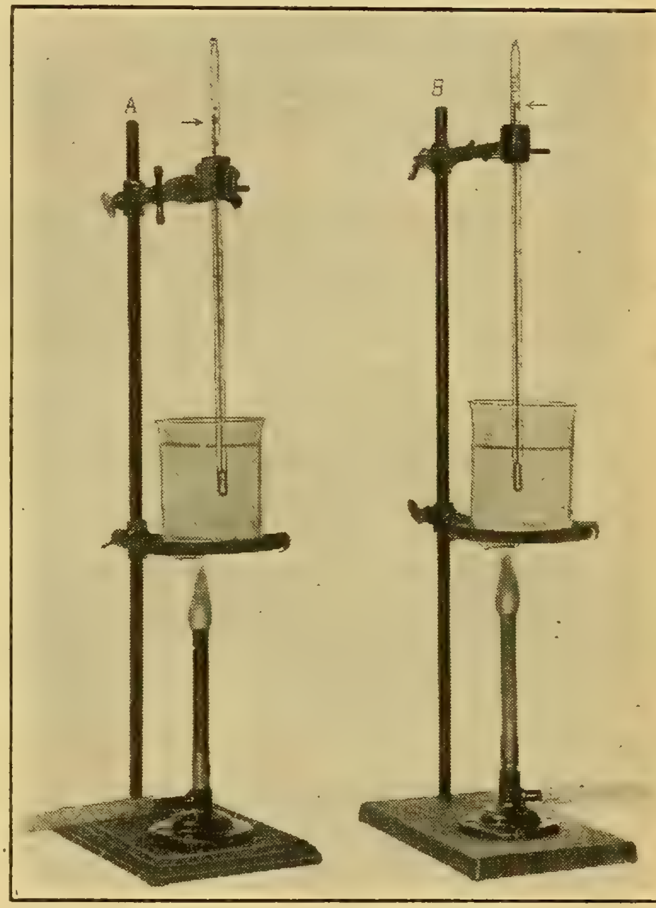


FIGURE 197. — BOILING POINTS OF WATER (*A*) AND SUGAR SOLUTION (*B*).

The latter is several degrees higher.

135. Effect of Dissolved Solids on Boiling Point. — In making certain kinds of candy, one dissolves a cup of sugar in boiling water from a tea kettle and then brings the sugar solution to a boil. Even allowing for the cooling effect of the sugar added, the sugar solution does not reach its boiling point for some time. A thermometer placed in the boiling solution of sugar shows a temperature higher than 100° (Figure 197). The boiling point of the water has been raised by the substance dissolved in it. Other soluble substances have a similar effect on the boiling point of water, provided fairly dilute solutions are used. In general, it may be stated

for dilute solutions, that *the elevation of the boiling point of a solvent is proportional to the amount of the dissolved substance.*

Five things to be remembered about the boiling of a liquid are:

(1) Heat is required to change a liquid to a vapor.

(2) The vapor pressure of a liquid at its boiling point equals the pressure of the atmosphere.

(3) The temperature of a boiling liquid and its vapor are the same.

(4) Increased pressure on a liquid raises the boiling point; decreased pressure lowers the boiling point.

(5) Dissolved substances raise the boiling point of the solvent.

136. Condensation and Latent Heat. — Every one is familiar with the heating and scalding effects of steam. The reason why steam is able to give off so much heat is that it *condenses, i.e.* changes back into a liquid, when it touches cool objects. During condensation it liberates a quantity of heat exactly equal to that which the water took in while evaporating (§ 130). In the gaseous state the steam particles retain the heat of vaporization as *latent,* or concealed, heat. The steam is *no hotter* than the boiling water from which it came, but it contains much *more heat* than an equal weight of boiling water.

The same principle holds good for all liquids: they require or take in heat in order to become vapors; the vapors give off their latent heat of vaporization to other objects during condensation. *Latent heat of vaporization is the heat required to vaporize a gram of liquid, and is given off when a gram of the vapor condenses.*

A gram of steam liberates an amount of heat sufficient to raise 540 g of water 1° C (§ 130). The severe scalding by

steam is not due so much to the contact with vapor at 100° as to the large amount of latent heat set free in condensation. In heating houses by steam, the radiators become hot from the condensation of the steam. The following experiment shows the relative heating effects of equal weights of steam and boiling water on equal masses of cold water.

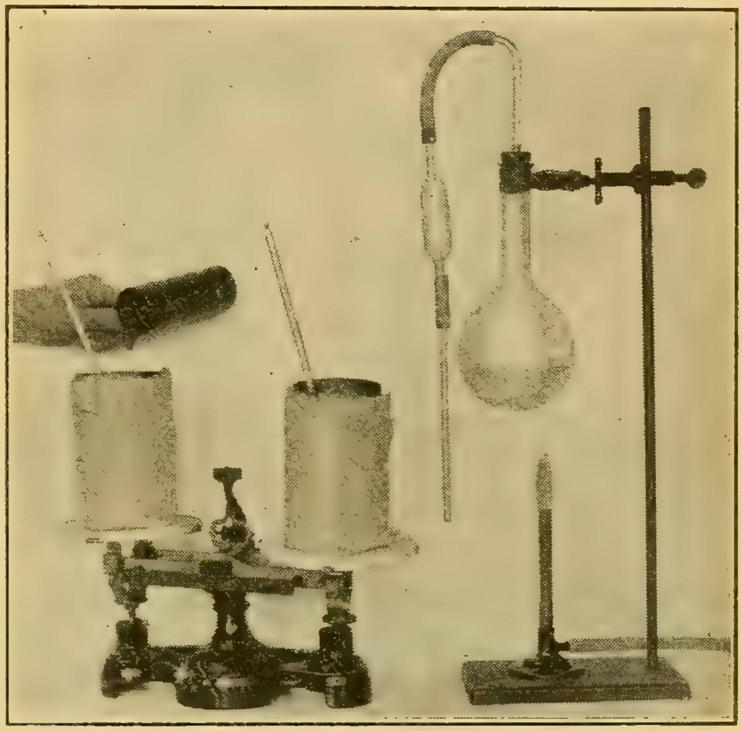


FIGURE 198. — The boiling flask at the right furnishes the steam and the steam trap in the delivery tube prevents any condensed steam from entering the calorimeter.

EXPERIMENT 56. — Balance two metal calorimeters on the pans of a platform balance (Figure 198). Pour equal weights of cold water into the two calorimeters. Pass steam from a boiling flask into the water of one of the calorimeters until the temperature rises to about 60° C. Pour enough boiling water from the flask into the other calorimeter to restore the balance. Take the temperature of the water in the two beakers. *Which of the two equal masses of cold water has been heated the more? Compare the heating effect of steam at 100° with that of boiling water at 100°.*

137. Distillation. — The two steps in the distillation of a liquid are vaporization and condensation. Condensation is usually accomplished by passing the vapor through a tube kept cool by water circulating through an outer jacket (Figure 199). Sometimes the tube is curved, as in the worm condenser (Figure 200), so as to increase the condensing area.

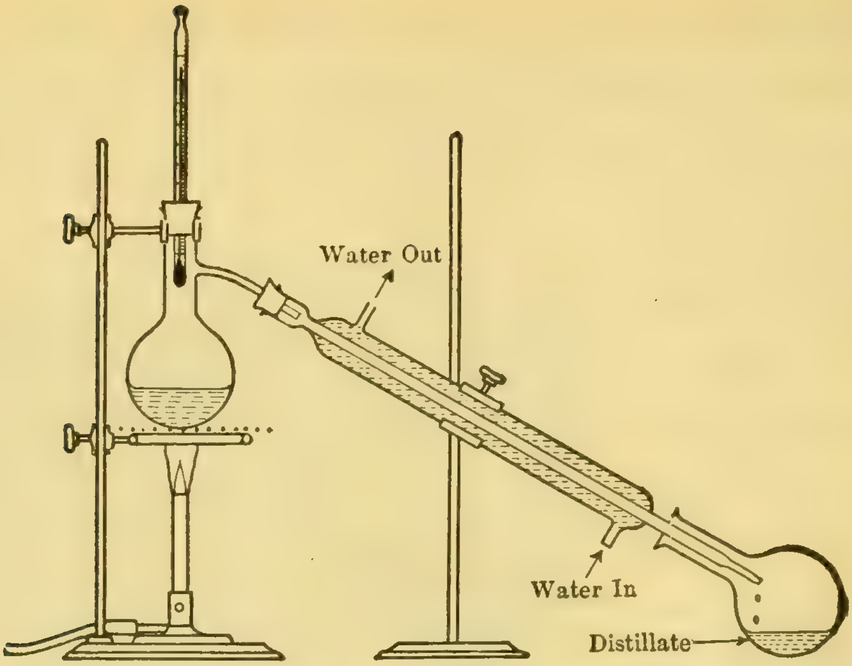


FIGURE 199. — Vapor passes through a tube that is surrounded by a stream of cold water, and this is condensed again to liquid. Any solid non-volatile impurities are left in the flask.

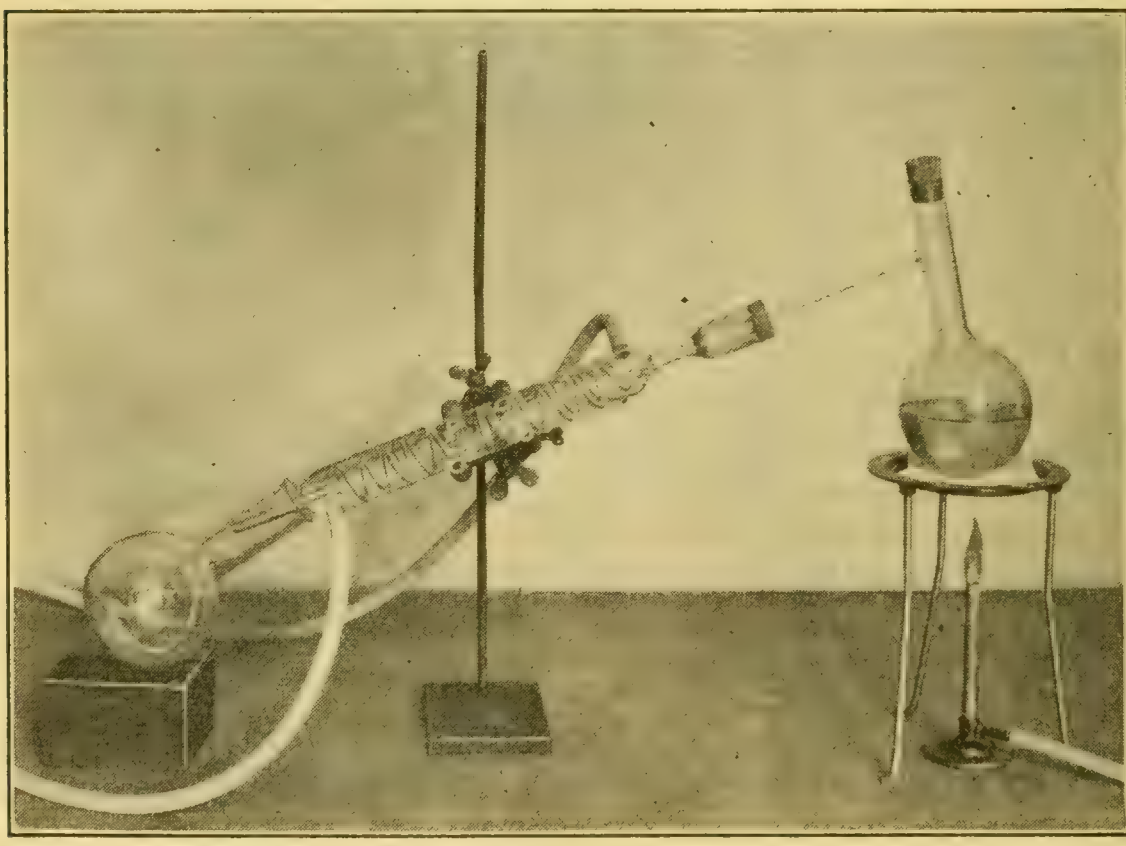


FIGURE 200. — A STILL WITH A COILED WORM.

Coiling the inner tube gives a much greater condensing area without increasing the length of the jacket.

Distillation is useful in purifying liquids from other substances that do not vaporize readily. Thus salt water can be made fit for drinking, since the non-volatile salt remains behind in the boiling flask. Ether, chloroform, alcohol, and other valuable solvents used in manufacturing operations, can be recovered by distillation from waste solutions containing them.

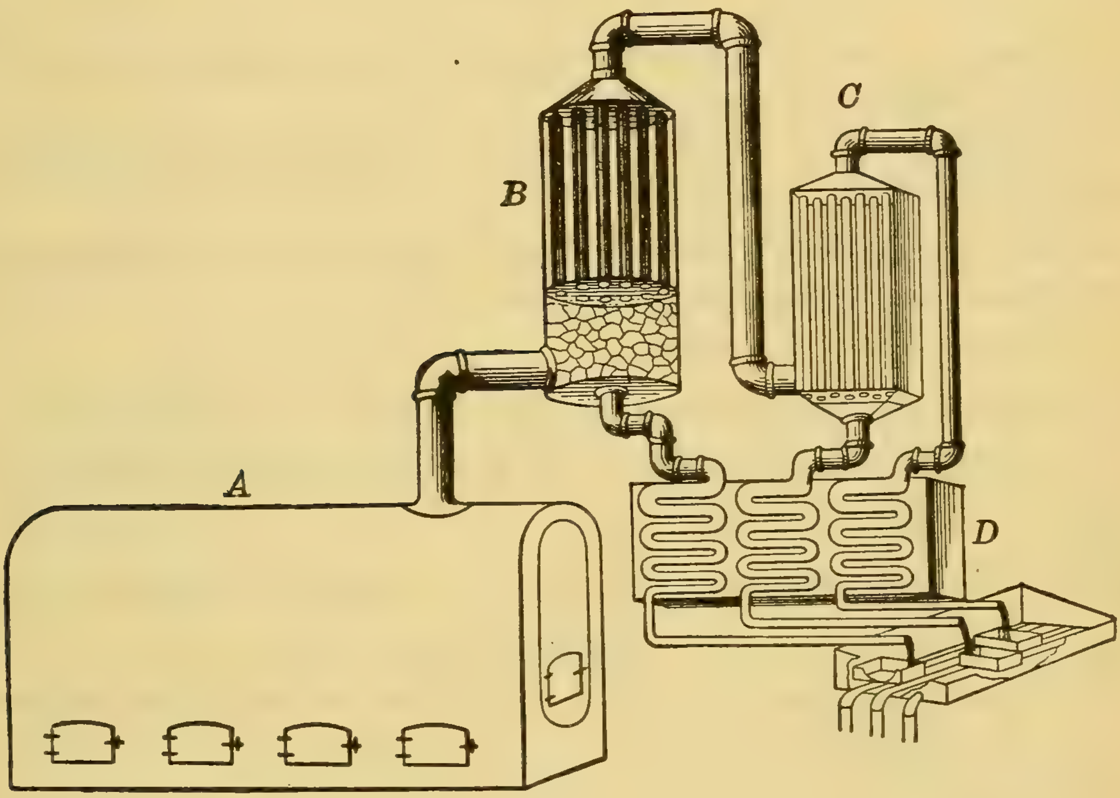


FIGURE 201. — REFINING PETROLEUM.

A, still; *B*, *C*, air condensers; *D*, water cooled condensers; *E*, distributing sink. Three products, having different boiling points, are separated at the same time.

Distillation can be used to separate liquids of different boiling points even when these are not far apart. When a mixture of alcohol and water is boiled, the first portions of the distillate (condensing liquid) are relatively richer in alcohol than in water; the later distillates are nearly all water. By redistilling the first distillates or fractions, a liquid con-

taining a still higher percentage of alcohol is obtained. Such a process is *fractional distillation*. By this process gasoline, benzine, kerosene, and other valuable products are obtained from petroleum (Figure 201).

QUESTIONS

1. Define *vaporization* or *evaporation*. At what temperature does it occur? What determines its rate?

2. Describe, in terms of movements of molecules, what happens when a liquid is evaporating.

3. What happens to a surface from which a liquid is evaporating? Describe an experiment that shows this.

4. Define *heat of vaporization*.

5. Discuss four factors that determine the rate of evaporation.

6. Describe the phenomena of boiling from the time that cold water is heated in a glass flask until steam escapes freely from the delivery tube.

7. At what pressure does water boil at 100° C? What is the effect on the boiling point of increasing the pressure?

8. Describe an experiment to show the effect of an increase of pressure on the boiling point.

9. How is the increased pressure obtained in a high-pressure steam boiler?

10. What are pressure cookers and what are their advantages?

11. Describe an experiment to show the effect of decreased pressure on the boiling point of a liquid.

12. Why does water boil below 100° C on a mountain?

13. Calculate the boiling point of water when the atmospheric pressure is 745 mm.

14. Why does not boiling water become hotter than 100° C when heat is applied more rapidly?

15. What is *condensation?*

16. What is meant by the *latent heat of steam?* What relation does it bear to the heat of vaporization?

17. Which causes the more serious burns, steam at 100° C or water at 100° C? Why?

18. State five important things to be remembered regarding the boiling of a liquid.

19. Name the two steps in the distillation of a liquid. What change of state occurs in each?

20. What are some of the practical uses of distillation?

21. What is fractional distillation? Give some of its practical uses.

138. Liquefaction of Gases. — In general, a gas may be condensed to a liquid either by cooling it or by subjecting it to increased pressure. By cooling and compressing certain gases at the same time, it is often possible to liquefy them without applying very great pressure or cooling to a very low temperature.

For each gas, however, there is a temperature, known as the *critical temperature,* above which no amount of pressure will change it to a liquid. Thus it is impossible to liquefy carbon dioxide above its critical temperature of 31° C by the application of any pressure whatever. The pressure needed to liquefy a gas at its critical temperature is *critical pressure.* The critical pressure of carbon dioxide is 73 atmospheres. The more a gas is cooled below its critical temperature, the less pressure is required to liquefy it. Thus at a temperature of − 80° C, carbon dioxide will liquefy at atmospheric pressure. The temperature of − 80° C is the boiling point of liquid carbon dioxide at atmospheric pressure.

The table on page 218 shows the critical temperature, the critical pressure, and the boiling point of certain substances.

All gases have now been liquefied, although some, like hydrogen and helium, baffled for years all attempts to condense them, since low enough temperatures could not be reached. The problem was solved, however, by taking advantage of the great cooling effect obtained by the rapid

Substance	Critical Temperature, Degrees C	Critical Pressure, Atmospheres	Boiling Point of Liquid at Atmospheric Pressure, Degrees C
Helium	− 268°	23	− 268.8°
Hydrogen	− 234°	20	− 252.8°
Air	− 140°	39	− 182°
Oxygen	− 118°	50	− 182.7°
Carbon dioxide	+ 31°	73	− 80°
Ammonia	+ 130°	115	− 8.5°
Water (dry steam) . . .	+ 365°	200	+ 100°

expansion of a highly compressed gas. The rapid expansion at a low pressure of part of the compressed gas gave a temperature low enough to make the rest of it liquid (Figure 202). The evaporation of one liquefied gas aided in the condensation of one that liquefied with greater difficulty. In this way, lower and lower degrees of temperature were attained, till finally even hydrogen and helium were obtained as liquids. Liquid hydrogen gave a temperature of − 252° C and liquid helium, − 272.18°. This last temperature is only 0.82° from the Absolute Zero.

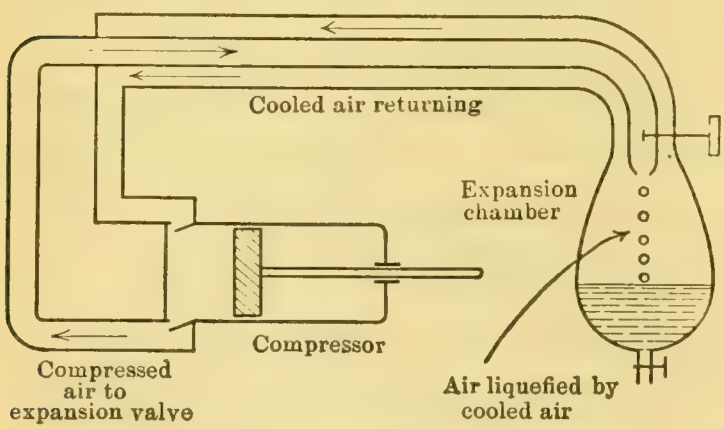


Figure 202. — Making Liquid Air.

A water-cooled condenser, for removing the heat of compression, and an inlet to the compressor for additional air are omitted for simplicity.

A supply of liquid air has made possible the conduction of many experiments at very low temperature. In some industrial plants, air is liquefied to get a supply of liquid oxygen

necessary for certain processes. The nitrogen boils off first, leaving the liquid oxygen. In other manufacturing plants, both the liquid nitrogen and the liquid oxygen are utilized for the manufacture of certain chemicals.

139. Artificial Ice and Refrigeration. — Ammonia is the substance most frequently employed in the manufacture

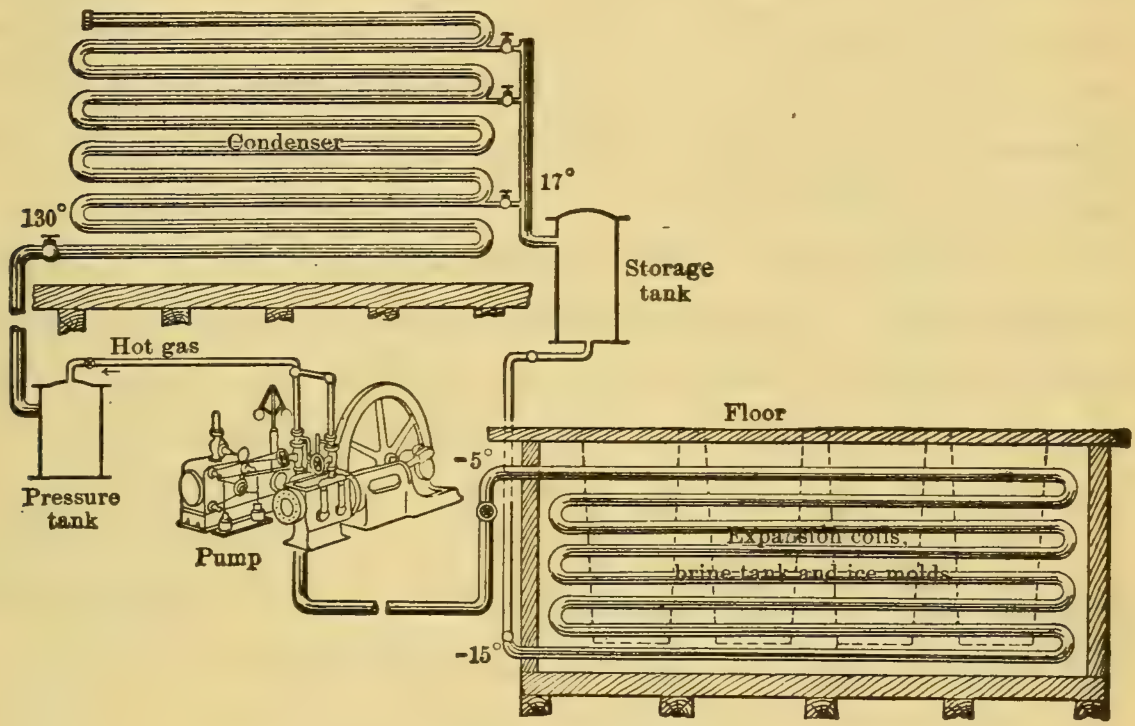


FIGURE 203. — ICE MACHINE.

The operation of this machine depends on the fact that liquids, in passing into the gaseous state, absorb heat. Note temperatures at all points.

of artificial ice. Below its critical temperature of 130° C, only pressure is needed to liquefy ammonia gas, and at a temperature of 26.6° C (80° F) a pressure of 10 atmospheres is sufficient.

In the making of ice (Figure 203), powerful pumps compress the ammonia gas, which is then cooled and liquefied by passing cold water over the pipes containing the compressed gas. The liquid ammonia is next run into the expansion coils that are immersed in a concentrated solution of salt or of

calcium chloride. The ammonia rapidly evaporates in the expansion coils and the heat required for its change from the liquid to the gaseous state is taken from the salt solution. This is cooled below the freezing point of pure water. Cans of water are placed in the cold brine, and the water is frozen in from 24 to 36 hours. The pumps aid in the rapid evaporation of the ammonia in the expansion coils, by exhausting the ammonia gas as fast as it is formed and keeping the pressure in the coils down to a little over one atmosphere. The ammonia returning to the pump is again compressed for use in another cycle of operations.

The cold brine from an ice-making plant is often circulated through pipes to provide refrigeration for the cold-storage rooms of markets and hotels, as well as the refrigerators of apartment houses. In some cases, refrigeration is obtained by circulating liquid ammonia. Several of the "electric" refrigerators of recent years are miniature ice-making plants in which a small motor runs the pump for compressing the ammonia, or other easily compressed gas.

QUESTIONS

1. In what ways may a gas be liquefied?

2. Define the *critical temperature* and the *critical pressure* of a gas.

3. Explain how very low temperatures can be obtained with highly compressed gases. State two of the lowest temperatures that have been reached in this way.

4. Of what practical importance is liquid air?

5. Why is ammonia gas selected for the making of artificial ice?

6. Make a diagram of a plant for making artificial ice. State what occurs in each part of the plant.

7. How is the refrigeration of cold-storage rooms obtained?

8. Describe an "electric" refrigerator for household use.

Weather Phenomena

140. Humidity. — The amount of water vapor in the air is known as its *humidity.* When the air is clear and dry, the humidity is low. Then clothes dry quickly on the line and water soon dries from the ground. When the humidity is high, as in the sultry days of midsummer, perspiration evaporates slowly from the skin and our clothes become unpleasantly moist.

The number of grams of water vapor per cubic meter of air at a given temperature is known as the *absolute humidity* of the air at that temperature. Thus, if air at 20° C (68° F) is saturated with water vapor, it contains 17.1 grams of water vapor in each cubic meter. If air at 20° C contains only 11.4 grams of water vapor per cubic meter, it holds only $\frac{11.4}{17.1}$, or 67% of the amount necessary for saturation. In the weather report of the daily newspaper, the humidity of such air would be given as 67. The humidity of the weather reports is *relative* humidity and is expressed in percentages.

Relative humidity is the ratio between the amount of water vapor in the air at a certain temperature and the amount necessary to saturate it at that temperature.

The humidity of the air is determined by a pair of thermometers exactly alike and known as the wet- and dry-bulb thermometers (Figure 204). The wet bulb is covered with cotton wicking, the lower end of which dips into a water reservoir. The wet bulb is cooled by evaporation from the wicking, and its mercury reading is accordingly lower than that of the dry bulb. The thermometers are placed where the air circulates freely and the temperature of both is read.

These readings do not give directly either the absolute or the relative humidity. These quantities are obtained by the use of tables based on the readings of the two thermometers.

The humidity of the air is a decided factor in our bodily comfort, our physical energy, and in our mental efficiency. Usually the air of our heated homes in winter is too dry and in such great contrast with the outside air that we are subject unnecessarily to colds and other affections of the respiratory tract. It has been stated by health authorities that the average humidity of the air at 72° F in houses heated by steam or hot water is 28%, while with hot-air furnaces it is 24%. The humidity of the desert air at the same temperature is about 30%. In heating schools and other places of public assemblage, the warm air is sprayed or passed over wet hangings, so as to give a proper degree of humidity before it is led into the rooms. Warm air can still be comfortable although the humidity is over 50%, while a small amount of water vapor can give cold air a relative humidity that makes the air clammy and disagreeable. The success of many manufacturing operations, such as cloth

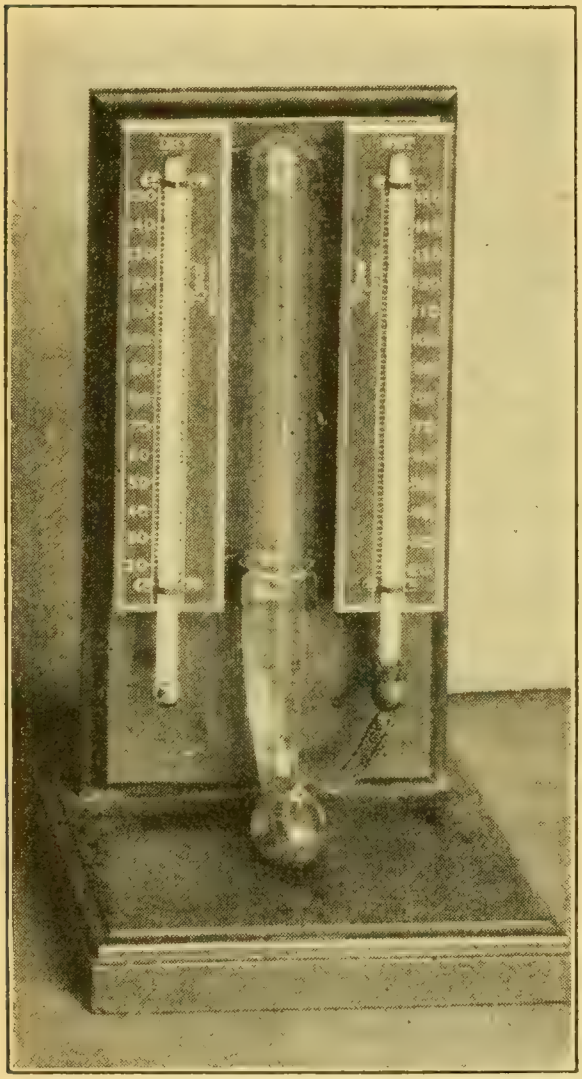
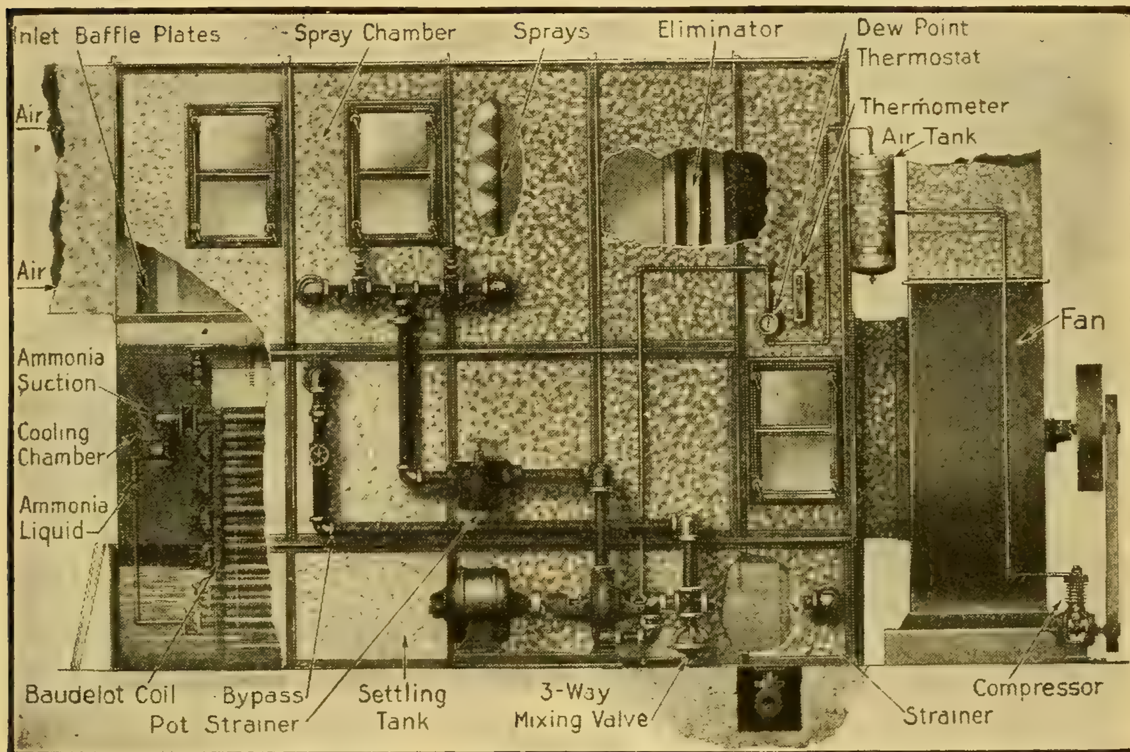


FIGURE 204. — WET- AND DRY-BULB THERMOMETERS.

Wet, right; dry, left.

manufacture and candy making, is dependent upon the proper humidity of the air, and suitable temperature and humidity are secured by air-conditioning apparatus (Figure 205).

141. Dew Point. — On a hot day the outside of a pitcher of ice water becomes coated with a thin film of moisture. The warm moist air is chilled by coming in contact with the



Courtesy of the Carrier Engineering Corporation.

FIGURE 205. — AIR-CONDITIONING APPARATUS.

Definite humidity of the air is secured by the spray and the ammonia cooling coil.

pitcher, and some of the water vapor in the air has to condense, since cold air cannot hold as much water vapor as warm air. When the vapor-saturated air of a summer day touches the rapidly cooling ground at nightfall, condensed vapor is deposited as dew on the grass. The temperature to which air must be cooled to produce condensation of water vapor is known as the *dew point.* The dew point varies with the amount of water vapor in the air.

A convenient way to determine the dew point is to put a little ether into a highly polished metallic cup (Figure 206). Air is blown through, and as the ether evaporates, the temperature is taken with a thermometer. The thermometer is read at the moment a thin film of moisture appears on the polished surface of the cup and again when the mist just disappears upon warming. The average of the two readings gives the dew point of the surrounding air.

FIGURE 206.—DEW-POINT APPARATUS.

The rubber bulb at the left pumps air through ether in the polished cup. Ether vapor condenses in the glass bulb and tube.

142. Rain, Snow, and Hail. — The heat of the sun absorbed by the ground during the day is rapidly lost by radiation at night, so that the overlying moist air is often cooled to its dew point or below. On clear summer nights the condensed vapor is deposited as dew, but when the temperature is lower it appears as *frost* if the ground cools to 0° C (32° F).

Clouds are masses of condensed vapor formed by the cooling of ascending columns of moist air. Minute drops of water or sometimes tiny bits of ice compose the clouds. These disappear if the air about them becomes warm enough to vaporize again the " water dust " of which they are made. *Fog* is a cloud very near the earth.

Rain results when ascending moist air is cooled to its dew

point. When warm, moist winds are forced up over mountains, they become cooled by expansion and by mixing with cold upper air. The moisture is condensed and precipitated as rain or snow.

Sleet is frozen rain and strikes the ground as ice particles. If condensation occurs below the freezing point, crystalline particles of snow are formed.

Hailstones are concentric layers of ice and usually occur with thunder storms. "*Ice storms*," often incorrectly called sleet storms, occur after a prolonged period of cold weather has cooled the ground, walks, and other exposed surfaces below the freezing point. When a warm humid wind sets in and strikes the chilled surfaces, condensed vapor forms a smooth coating of ice. The same effect may result if rain strikes the chilled surfaces.

QUESTIONS

1. What is meant by the *vapor pressure* of a liquid? When is a vapor said to be in equilibrium with its liquid? When is the air above a water surface *saturated* with water vapor?

2. How does temperature affect the pressure of water vapor? Give examples.

3. What is meant by the *humidity* of the air?

4. Define *absolute humidity.*

5. What is *relative humidity?* How is it expressed?

6. Describe the wet-bulb and the dry-bulb thermometers. What use is made of their readings?

7. In what ways does the humidity of the air affect us?

8. Discuss the conditions of humidity that prevail in the average house in winter.

9. How is the proper humidity of the air secured for schools and places of public assemblage?

10. Why may the cold air of winter be very disagreeable, although the percentage of humidity may not be very high?

11. What is the *dew point* of the air? Describe an experiment by which it can be determined.

12. Explain the formation of *dew* and of *frost.*

13. Distinguish between clouds and fogs.

14. How does rain occur?

15. What is sleet? State the conditions that lead to "ice storms."

SUMMARY

Every **change of state** of a substance means a change in the activity of its molecules. If the molecular activity becomes greater in the change, heat is absorbed; if the molecular activity becomes less, heat is liberated.

Fusion or melting is the change from the solid to the liquid state. The **heat of fusion** of a substance is the heat required to melt a gram of the solid substance without changing its temperature. **Crystalline substances have definite melting points**, while the melting points of many amorphous substances cannot be determined within several degrees.

Heat is absorbed in dissolving most substances in water. In cases where heat is liberated, this is probably due to chemical reactions.

Freezing or solidification is the change from the liquid to the solid state. During this change **heat is given off**, making the surrounding objects warmer.

The depression of the freezing point of the solvent in dilute solutions is proportional to the amount of the dissolved substance.

Freezing mixtures are applications of the depression of the freezing point of a solvent. The heat required for the melting of the solvent in its solid form is taken from the solution and other objects in contact with it. Any mixture of salt and ice has a definite limit to which the freezing point of water can be depressed, depending upon the relative amounts of salt and ice.

Increased pressure raises the melting point of substances that contract on freezing, and lowers the melting point of substances

that expand on solidifying. **Regelation** is the process of melting ice by means of increased pressure, and the subsequent refreezing of the water as it flows out of the region of increased pressure.

Some substances contract when they solidify while others expand.

Evaporation is the flying off of molecules of a liquid from its surface. **A liquid is in equilibrium with its vapor** when the number of molecules returning to the surface of the liquid is equal to the number leaving it. Then the space above the liquid is said to be **saturated** with the vapor. **The vapor pressure** of water increases with the temperature. At the boiling point of water, its vapor pressure is equal to atmospheric pressure. **The evaporation of a liquid is favored by four conditions**: (1) an increase in temperature; (2) an increase in the area of the surface from which the evaporation occurs; (3) a decrease in pressure over the evaporating surface; and (4) the change of air over the liquid surface.

An evaporating liquid absorbs heat from the objects around it and these become cooler. Evaporation takes place against the pressure of the atmosphere. **The heat of vaporization** of a substance is the heat required to change 1 gram of the substance from a liquid to a gas.

The boiling point of a liquid is the temperature at which its vapor pressure is equal to the atmosphere pressure.

The **elevation of the boiling point** of a solvent in dilute solution is proportional to the amount of the dissolved substance.

Five facts characterize the boiling of a liquid: (1) Heat is required to change a liquid to a vapor; (2) The vapor pressure of a liquid at its boiling point equals the pressure of the atmosphere; (3) The temperature of a boiling liquid and of its vapor are the same; (4) Increase of pressure raises the boiling point; and (5) Dissolved substances raise the boiling point of the solvent.

The boiling point of a liquid is raised by an increase in pressure and lowered by a decrease in pressure. A change in pressure of

10 mm of mercury makes a change of 0.37° C in the boiling point of water at 100° C.

The **latent heat** of steam is the heat liberated when steam condenses to water. It is the same heat that changes the water to steam.

The two steps in **distillation** are vaporization and condensation. Distillation is **used** to free liquids from non-volatile impurities. **Fractional distillation** is used to separate liquids of different boiling points. Petroleum is refined by this process.

A gas may be liquefied either by cooling it, by subjecting it to increased pressure, or by doing both.

The critical temperature of a gas is that temperature above which no amount of pressure will change it to a liquid.

The critical pressure of a gas is the pressure needed to liquefy a gas at its critical temperature.

All gases have been liquefied. By the evaporation at a diminished pressure of gases previously compressed and cooled, the lowest degrees of temperature have been obtained.

Artificial ice is made by immersing cans of water in a brine cooled to a low temperature by the evaporation of liquid ammonia in pipes that run through the brine.

Humidity is the amount of water vapor in the air. It depends upon the rate of evaporation of water. On clear, cool days, the humidity is low; on sultry days, it is high. **Absolute humidity** is the number of grams of water vapor per cubic meter of air at a given temperature. **Relative humidity** is the ratio between the amount of water vapor in the air at a certain temperature and the amount necessary to saturate it at that temperature. It is expressed in percentages, as in the weather reports.

Relative humidity is found by the use of two thermometers, the dry-bulb and the wet-bulb. The difference between the readings of the two thermometers, used in connection with a table, gives the percentage of humidity. The humidity of the air decidedly affects our bodily comfort, our physical and our mental

activity. A much lower percentage of humidity makes cold air more disagreeable than warm air with the same relative amount.

The dew point is the temperature to which air must be cooled in order that condensation of water vapor may occur.

Dew is the condensed vapor of the air deposited on the earth's surface cooled by radiation. When the surface cools to 0° C or below, **frost** is formed. **Clouds** are masses of condensed vapor formed by the cooling of ascending columns of moist air. **Rain** results when the ascending moist air is cooled to its dew point. **Sleet** is frozen rain. If condensation occurs below the freezing point, crystalline particles of snow are formed. **Hailstones** are concentric layers of ice formed under unusual conditions in the air above us.

EXERCISES

1. What term is applied to the heat required to melt 1 gram of ice at 0° C?

2. Which has the greater amount of heat, 1 gram of ice at 0° C or 1 gram of water at 0° C? Which has the greater molecular energy?

3. Is ice or ice water the better refrigerant? Explain.

4. Why does the temperature of the air have to rise considerably above 0° C to melt a fall of snow quickly?

5. What noticeable effect is produced on the temperature of a glass vessel in which a water solution of "hypo" is made? What is the reason for this?

6. Compare the melting point and the freezing point of a substance.

7. Explain how a mixture of ice and salt produce a temperature low enough to freeze ice cream.

8. How does salt melt the ice on trolley car tracks in winter?

9. Why do harbors on the seacoast remain open in winter, while nearby inland lakes freeze?

10. Explain the packing of snow on a much traveled highway.

11. Show how regelation aids a glacier in moving around a bend in its path.

12. What property of cast iron enables it to take the impression of the mold into which it is poured?

13. How does the freezing of water in the crevices of rocks aid in the formation of soil?

14. Does the evaporation of a liquid absorb or release heat? Do surrounding objects become warmer or cooler?

15. Account for the cooling of drinking water in the porous earthenware jars used in warm countries.

16. What term is applied to the heat required to change a liquid to a gas?

17. Why does heating make moist air dry?

18. Describe an experiment to show cooling by evaporation. Give the conclusion and state the reasons for it.

19. (*a*) Does the perspiration that results from violent exercise help to warm or to cool the body? Explain. (*b*) Why should a baseball pitcher put on a sweater when he goes to the bench?

20. Why does fanning cool a person? Is it more effective on dry or on sultry days?

21. Account for the rapid drying of wet city pavements on a windy day.

22. Why does blowing on the hands cool them, while breathing gently on them warms them?

23. What effect do wet shoes or wet clothing have upon the surface temperature of the body? Explain.

24. Iceless refrigerators are porous containers of water. What is the reason for their effectiveness?

25. Which possesses the greater amount of heat, 1 gram of steam at 100° C or 1 gram of water at 100° C? Why?

26. Which should be larger in order to heat a certain room, a steam radiator or a hot-water radiator? Why?

27. How does a steam radiator become heated in case the steam enters it and the water leaves it at the same temperature?

28. Describe the changes that occur when cold water is heated until it boils.

29. Why is it undesirable to have dissolved substances in the water of a steam boiler?

30. How can mercury be recovered from a mixture of mercury and zinc? Why?

31. Compare the thermometer reading taken inside a steam boiler at 130 lbs pressure with the reading taken above the boiling water in a teakettle. Explain.

32. What is the "pressure cooker" used in food canneries? Why is the food cooked in them more wholesome?

33. Describe, with the aid of a diagram, an experiment to show the effect of decreased pressure on the boiling point of a liquid.

34. Why would it be difficult on the top of a very high mountain to cook eggs by boiling?

35. Explain how intense cold is produced by the evaporation of liquid hydrogen.

36. State the effect of high relative humidity on *sensible* temperature (*a*) in summer; (*b*) in winter. Is New York City or Denver most affected by humidity?

37. Why is it difficult to keep cool on a hot day when the humidity is high?

38. Is the dew point fixed or variable? What results when the air outdoors reaches its dew point?

39. (*a*) What kind of nights favor the formation of dew? Explain. (*b*) When is dew not likely to form?

40. What causes the "sweating" on ice-water pitchers and cold-water pipes? Does this usually occur in summer or in winter? Why?

41. Account for the frosty coating on the outside of the brine pipes in a cold-storage room.

42. Why do moist winds from the Pacific lose their moisture as they ascend the mountains of California?

CHAPTER XII

SOUND AND SOUND WAVES

143. Origin of Sound. — Sounds may vary from the tick of a watch to the crash of thunder, yet all of them may be traced to something in vibration (Figure 207). Plucking sets the strings of a banjo in motion and produces the note. After a drum is struck, the finger can feel the drumhead vibrating. A bell continues to send forth sound as long as it vibrates. Touch the bell and the ringing ceases.

FIGURE 207. — A hacksaw blade held against the table gives vibrations that may be seen and heard.

EXPERIMENT 57. — Suspend a pith ball by a thread. Strike a tuning fork and touch it to the pith ball. *Why does the pith ball fly away each time that it touches the prong of the fork?*

When a tuning fork is struck, the prongs can be seen in motion, but the vibrations are too rapid to be counted. They can be demonstrated, however, and their frequency measured by the apparatus shown in Figure 208. A tuning fork of bell metal (F) carries a tubular ink pen (P) which marks the vibrations of the tuning fork upon a paper tape (T) mounted on a reel (R). To mark the time intervals

upon the tape, a pen is carried at the end of a rocker arm on a sounder (S) which is connected with a seconds pendu-

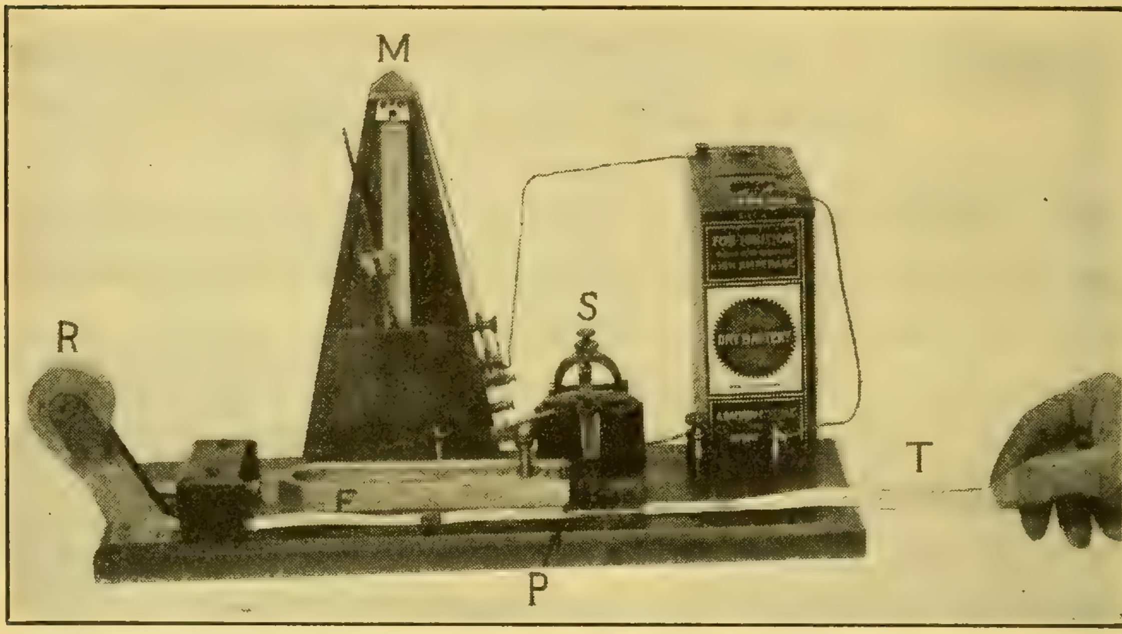


FIGURE 208. — Recording the vibrations of a tuning fork on a paper tape.

lum or metronome (M). The fork is set vibrating by a metal bar, which is a little longer than the space between the prongs of the fork. The vibrations of the fork are registered as a series of wavy lines upon the tape (Figure 209). Counting the number of these between the second or half-second intervals marked by the sounder gives the number of vibrations per second or the vibration frequency of the fork. Each vibration of the fork starts an impulse through the air.

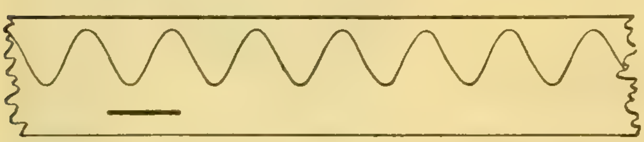


FIGURE 209. — TUNING FORK RECORD.

The wavy line is made by the pen on the fork and the straight line by the sounder.

EXPERIMENT 58. — Press the corner of a card against a rotating record on a phonograph machine. Note that as the sounds are produced, the card can be felt to vibrate.

144. Phonograph. — The original commercial phonograph was invented in 1879 by Thomas A. Edison. Like the dictaphone of to-day, it had a wax cylinder on which the vibrations of a diaphragm were recorded by a chisel-shaped metal point. This cut a spiral grove in the wax, and the indentations corresponded to the condensations and rarefactions of the sound waves impressed upon the diaphragm. When the chisel-pointed needle was replaced by one with a rounded point, which was then made to follow the indentations in the spiral groove (Figure 210), the diaphragm was caused to vibrate. These vibrations reproduced the original sound.

Courtesy of John Bellamy Taylor.

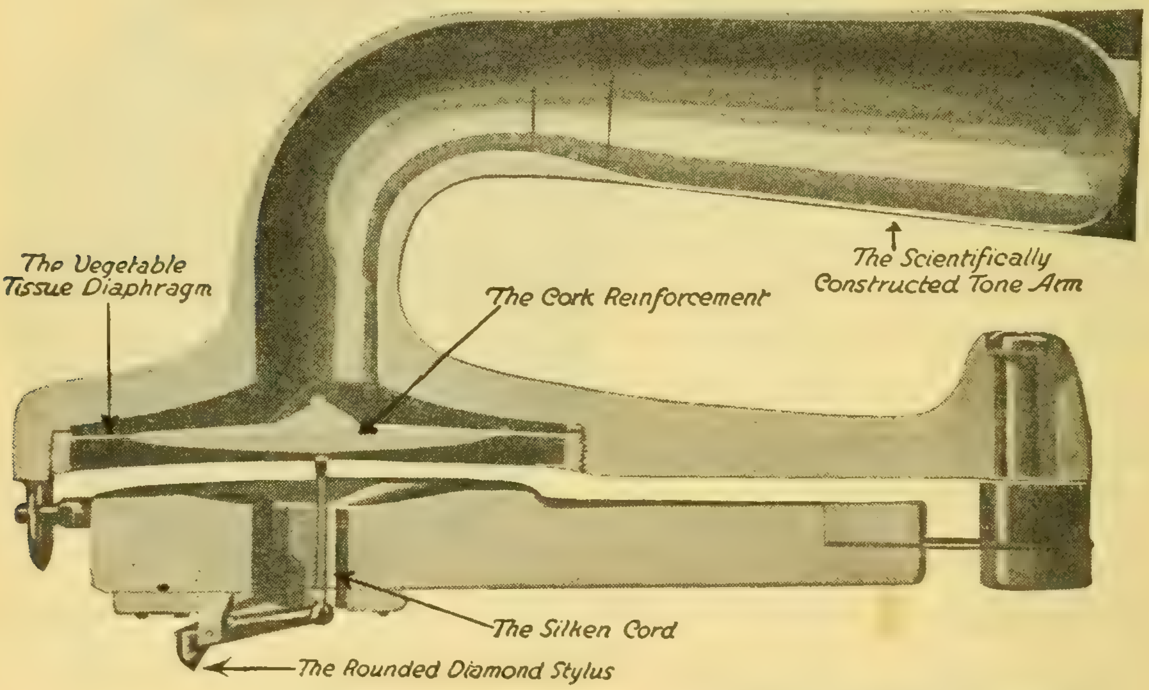
FIGURE 210. — MICROPHOTOGRAPH OF DISK RECORD.

The side to side indentations give motion to the needle, which causes the diaphragm to vibrate.

The phonograph record of to-day is made by recording sound vibrations on a circular disk of suitable material. A wax impression is taken of this record. The wax, in turn, is coated with graphite and an electrotype made from it. This is the master record. In making the master records of the songs of great artists like Caruso, the electrotypes are often of gold. Duplicates of a master record are made by taking casts of it with hard rubber or other plastic material. These duplicates are the records placed on sale.

The phonograph record is revolved in a horizontal position

by means of a spring motor or small electric motor. The needle, following the indentations in the circular grooves of the record, transmits its vibrations to the diaphragm. This in turn vibrates from side to side in its vertical position, reproducing the original sounds. Resonance is given to the reproduced tones by a horn or by the box or cabinet inclosing the phonograph. In the diamond-pointed phonograph, so



Courtesy of Edison Phonograph Co.

FIGURE 211. — EDISON REPRODUCER.

The vertical vibrations of the diamond point are magnified by the lever and are transmitted to the diaphragm by the silken cord.

named from the character of its needle, it is unnecessary to change the needle, and a further advantage lies in the mellower tone produced. In this type of phonograph, the indentations in the record are vertical and the diaphragm is horizontal (Figure 211).

145. Transmission of Sound. — All sound vibrations must be transmitted through some elastic medium to the ear before we can hear the sounds. The necessity of a

medium to transmit a sound from its source to the ear may be shown by placing an electric bell in a bell jar on an air pump plate (Figure 212). When the air in the jar is exhausted

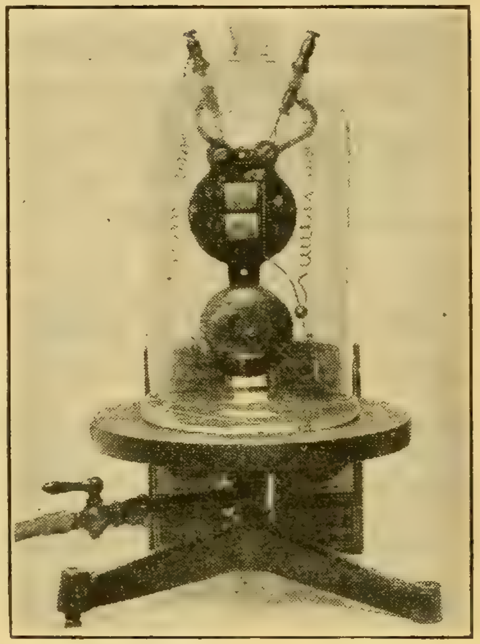


FIGURE 212.—BELL IN VACUUM.

The bell is hung by rubber bands to prevent its vibrations from being carried to the glass.

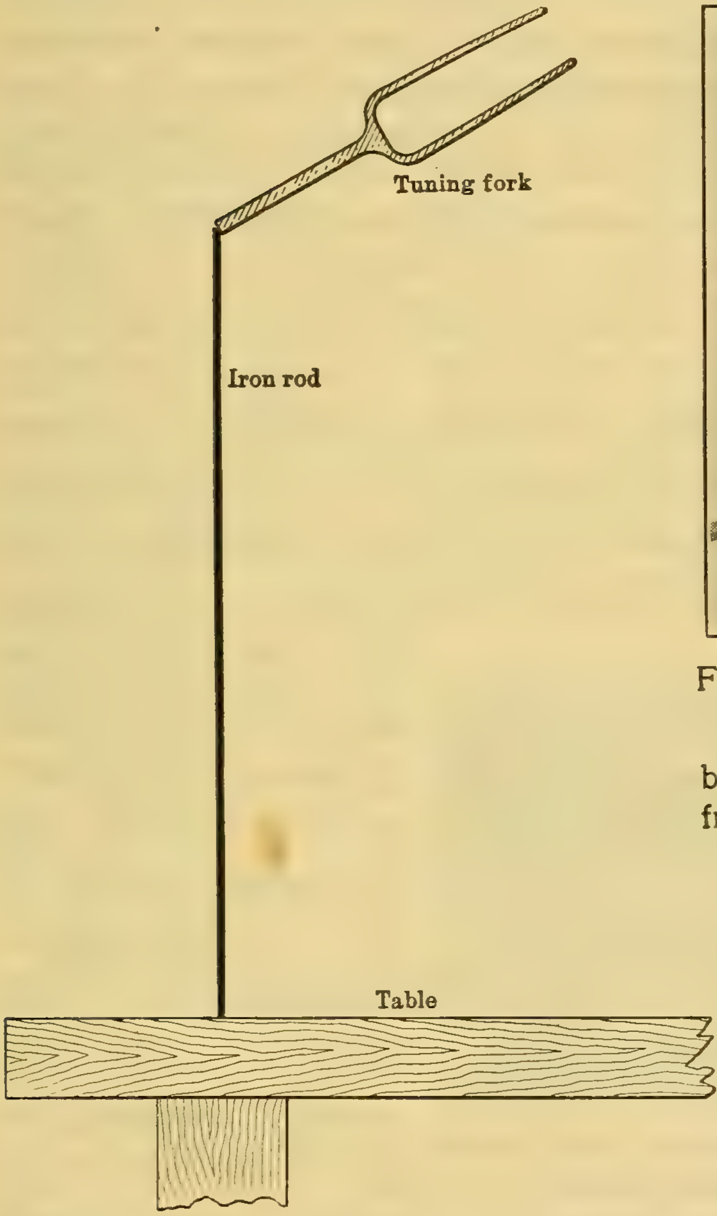


FIGURE 213. — The rod transmits the vibrations of the fork to the table. The vibrating table top sets a large amount of air in motion.

and the bell circuit closed, the hammer of the bell can be seen to strike the gong without any sound being heard. On admitting air to the jar, a faint ringing is heard which grows louder as more air enters. In the jar when the air had been exhausted, there was no medium to transmit the vibrations of the bell, so the ringing was not audible.

All elastic substances, whether solids, liquids, or gases,

transmit sound, but some convey it better than others. An experiment will illustrate this.

EXPERIMENT 59. — Use a large tuning fork as the source of sound. A resonance box or table top is used to amplify the sound produced by the fork. Strike the fork so as to make it vibrate and rest its handle on an iron rod with its lower end touching the table (Figure 213). *From where does the sound appear to come?* Repeat the experiment, using a wooden dowel rod and then a long rubber eraser. *In which case is the loudest sound heard? Which substance is the best transmitter of sound?*

One can hear through a log the scratching of a pin at the other end. The tapping of a hammer on a steam or water pipe in the basement may be plainly heard on the floors above. These are familiar examples of the transmission of sound by solids. In liquids, the striking together of two stones below the surface of water produces a sound painfully evident to the ears of a submerged person. A fisherman avoids making unnecessary noise for fear the transmitted vibrations will frighten the fish away. Air is the medium through which most sounds reach our ears, and it affords the best means of studying the transmission of sound.

FIGURE 214. — Waves spread in circles from the place where the stone strikes.

146. Waves. — Vibrations of many kinds are transmitted by waves. A stone thrown into a pond starts a series of circular waves that travel to all the shores (Figure 214). These waves are able to do work even at a distance from

the splash that started them. The heat that we receive from the sun is believed to be transmitted by waves. Without the wave theory for light, many optical effects would remain unexplained.

When we look at the wave-roughened surface of a sea or lake, we see a succession of crests and troughs. The distance from one crest to the next, or from one trough to the next, is the *length* of the water wave. The length may also be defined as the distance from a point in one wave to the corresponding point in the next wave. Such a series of crests and troughs can be pictured by a simple curve (Figure 215) that represents the transmission of a disturbance due to an energy impulse. Each wave consists of a crest and a trough.

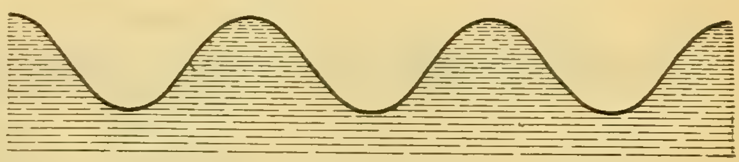


FIGURE 215. — WAVES OF CRESTS AND TROUGHS.

All waves, however, are not like water waves, since waves differ greatly in character. Some of the simpler kinds can be illustrated by experiments.

EXPERIMENT 60. — Attach one end of a long length of flexible rubber tubing to a hook in the wall. Give the free end a snap with the hand and note the disturbance that travels along the tube and back again (Figure 216). The general position of the tube remains horizontal, but the disturbance passes along the tube by means of up and down motions, called *transverse vibrations*.

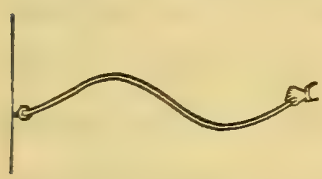


FIGURE 216.

Water waves are transverse waves. To an observer on the shore, a floating barrel is seen to bob up and down without getting any nearer, while the waves that disturb it advance rapidly toward the shore. The disturbance or wave motion is transmitted horizontally and at right angles to the transverse motions of the water.

The individual water particles in a wave, however, simply oscillate up and down as the wave passes, finally returning to rest at the same point at which they began to vibrate. One half of the vertical distance from crest to trough is the *amplitude* of the wave.

Waves of another kind are longitudinal or compression waves. These also can be shown by a simple experiment.

Experiment 61. — Fasten an elastic spring coil to a support on the ceiling and hang a weight on the lower end. Compress with the fingers a section of the spring near its lower end and then release it

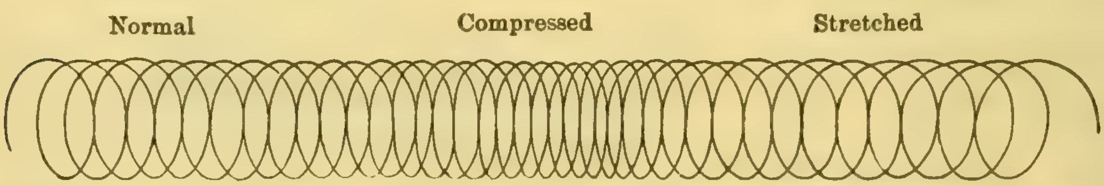
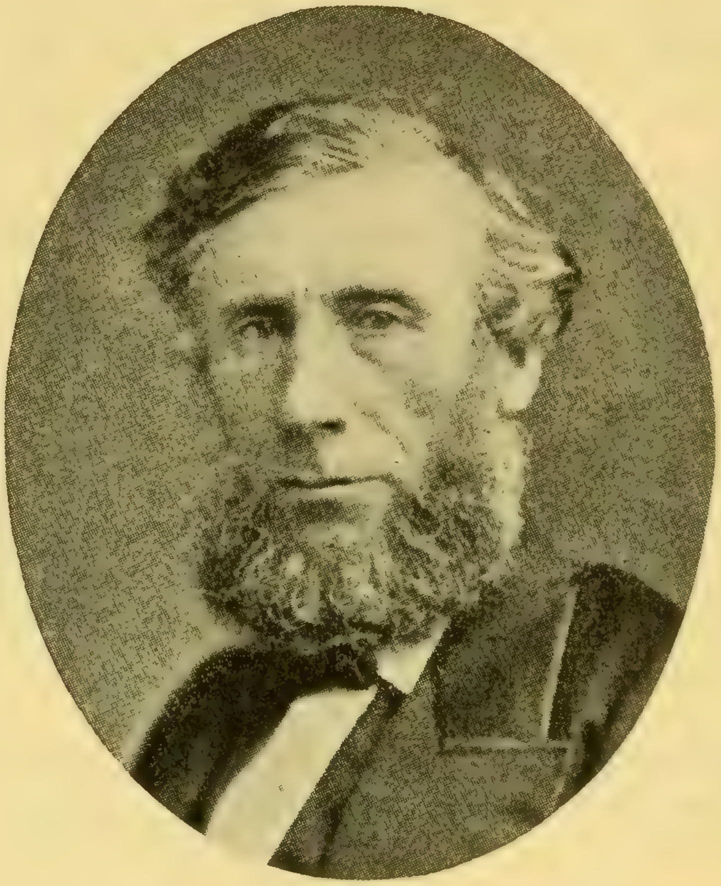


Figure 217. — Longitudinal wave in spring traveling from right to left.

(Figure 217). Note how the disturbance travels along the spring to the fixed end. *Why are such waves called longitudinal waves? Compression waves?*

In the experiment with the coiled spring, several coils were compressed with the fingers. When the pressure is released, the compression or *condensation* can be seen traveling along the spring, the compressed section transmitting an impulse to the coils immediately above, which in turn become compressed. The coils in the region from which the impulse has just passed tend to spread out as a result of reaction and there is a section where the number of coils is relatively fewer. This is known as a *rarefaction*. A condensation and rarefaction taken together constitute a *longitudinal wave.*

147. Sound Waves. — The sources of sound are elastic bodies producing vibrations that give rise to impulses in an elastic medium which are transmitted in all directions. For



John Tyndall (1820–1893) was a most popular professor of physics, a skillful experimenter, and a lecturer of great originality and power. Like many other scientists of note, his mind was busy with a multitude of subjects which range through light, heat, sound, magnetism, electricity, and various geological phenomena. In all these subjects we find the treatment of an able experimenter, a careful observer, and above all, an interesting recorder of physical facts. His personality did much to interest the general public in science, and to influence younger men of genius to become scientists. His books on "Sound," "Heat, A Mode of Motion," and "Fragments of Science" are clear, interesting, and capable of easy understanding.

this reason, the voice of a speaker can be heard on all sides and behind him as well as in front of him.

The impulses from vibrating bodies were early called *sound waves* from their resemblance to water waves. Sound waves, however, consist only of *longitudinal* vibrations in the direction that the sound is traveling. Their nature can be understood by the consideration of the behavior of a crowd gathered around some object of interest. When a policeman pushes the people back, those in the front line are crowded upon the persons immediately behind them. These in turn pass on the push to the next line and so the impulse is carried to the farther limits of the crowd. As soon as the impulse that crowds several lines together passes, these lines tend to spread apart a little. Hence at any one time in the crowd there are places where lines of people are pushed together and places where lines are spreading apart. The crowding together corresponds to the *condensations* and the spreading apart of the lines to the *rarefactions* of a sound wave. Similarly, a vibrating body transmits an impulse to the air particles immediately adjacent to it and these air particles, in vibrating, crowd upon other air particles near them, producing a condensation. When the vibrating body moves backward in the opposite direction, it leaves a space which the air particles surge backward to fill. This region where the air particles are relatively fewer is the *rarefaction* of a sound wave. Each sound wave consists of a condensation and a rarefaction. The vibrations of the sounding body set up a series of these waves that travel through the air and affect the ear, producing the sensation of sound.

Figure 218 shows a diagrammatic representation of a section of a sound wave. The *length* of a sound wave is the distance from one condensation to the next. A sound travels

its wave length during one vibration. The *amplitude* of a sound wave is the distance that a single particle is displaced

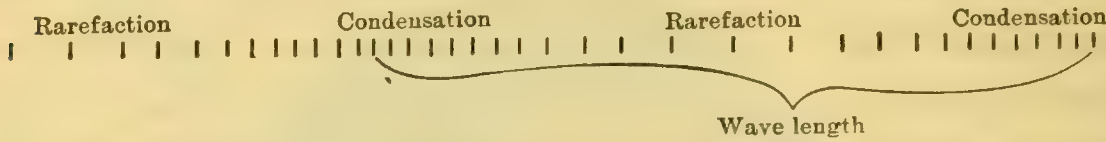


FIGURE 218. — A VERY THIN SECTION OF A SOUND WAVE.

The lines represent layers of air.

during the passage of the wave. Figure 219 shows a wave model machine, the disks representing air particles. The condensations and rarefactions are evident and the ampli-

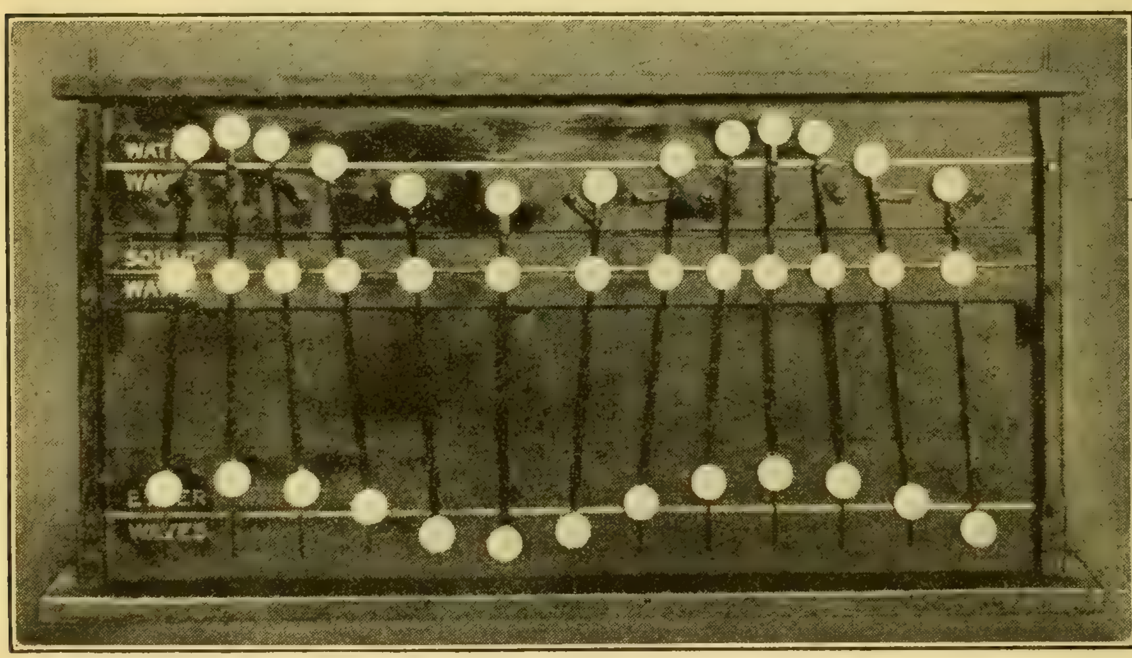
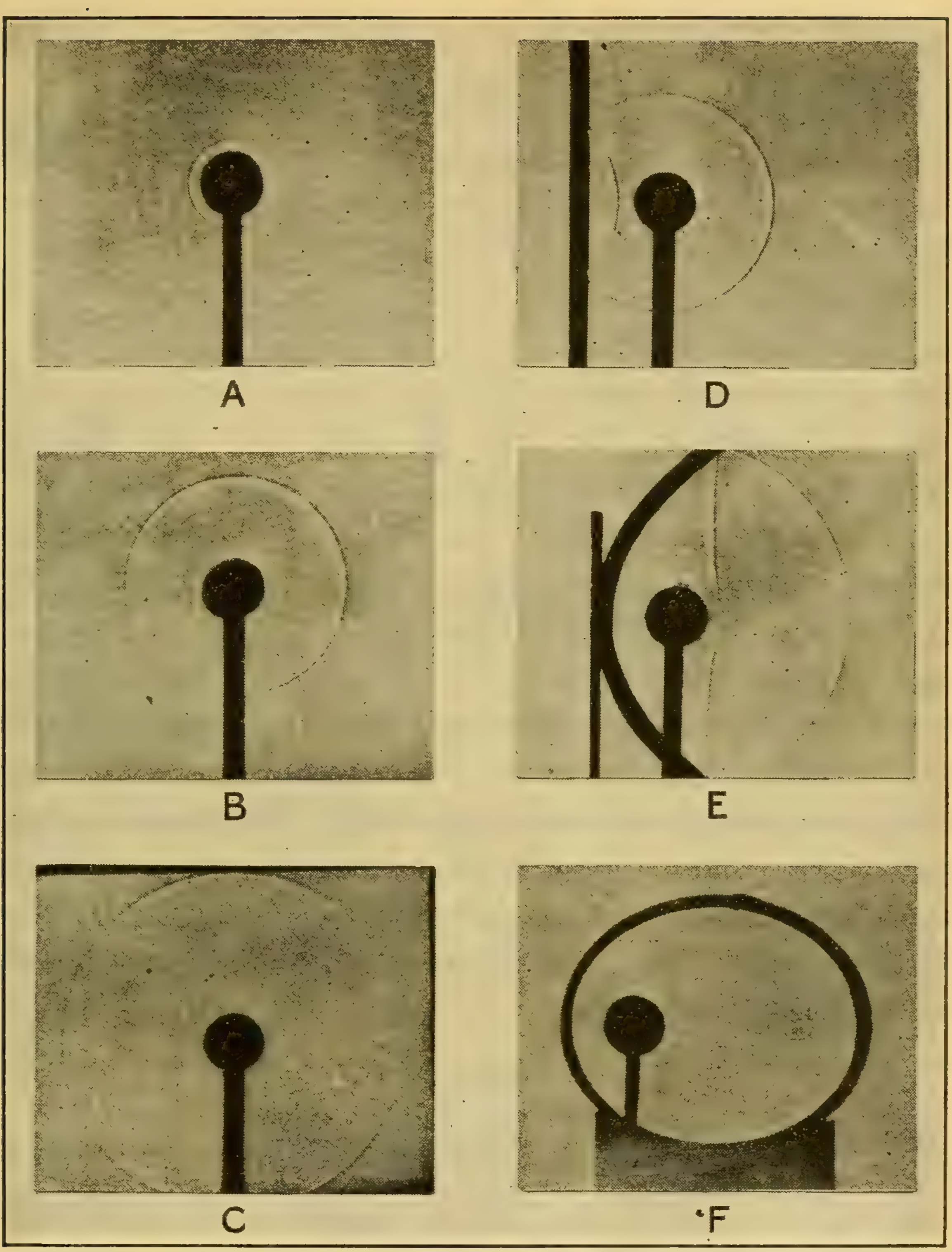


FIGURE 219. — WAVE MACHINE.

Turning a crank on the back causes the disks to oscillate. The sound wave in the center is contrasted with a water wave above and a transverse ether wave below.

tude is the distance that the particle has been moved between its two positions (Figure 221).

Figure 220 shows photographs of sound waves made by using the spark of an induction coil as the source of the sound. Condensed and rarefied air in the sound wave bend



Photographed by Professor Foley of Indiana University.

FIGURE 220. — SOUND WAVES PRODUCED BY AN ELECTRIC SPARK.

A, B, C. Three positions of wave a few thousandths of a second apart.
D. A flat surface gives a curved reflection of the wave.
E. A parabolic reflector makes the reflected wave plane.
F. The wave is brought to a focus by an elliptical reflector.

light from an arc lamp differently, producing an image on a photographic plate.

Enormous sound waves are sometimes started by the detonation of a large amount of high explosive. While only the buildings in the immediate vicinity of the explosion may be razed, thousands of window panes several miles away may be broken by the huge wave of atmospheric compression that spreads in all directions. In the case of such damage, it is noticeable that the broken glass usually falls into the street instead of into the building. The wave of compression or condensation bends the glass to its breaking point. Following the passage of the compression through the glass, comes a rarefaction. For an instant there is very little pressure outside on the glass, and the greater pressure within the building pushes the glass into the street.

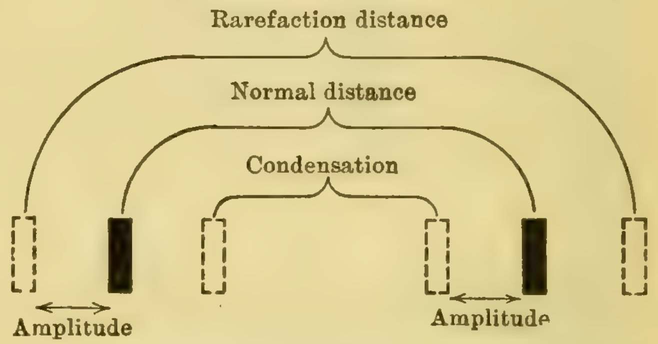


FIGURE 221. — A greatly enlarged view of the motion of an air particle. Dotted lines show extreme positions between which it oscillates.

QUESTIONS

1. Show that sound is produced by vibrations. Describe what occurs when a body vibrates in air.

2. What is meant by the vibration frequency of a tuning fork? Describe an experiment for determining it.

3. Describe an experiment that shows a medium is necessary for the transmission of sound.

4. Give illustrations to show that other media beside air transmit sound.

5. Compare several common substances as to their ability to transmit sound.

6. How is a water wave started? Of what two parts does it consist? What is its length?

7. State what is meant by *transverse vibrations*. Describe a simple experiment illustrating them.

8. Describe a simple experiment that illustrates longitudinal or compression waves. Of what does such a wave consist?

9. What are the sources of sound? In what direction is sound transmitted?

10. What kind of waves are sound waves? Of what does each consist?

11. Distinguish between the length and the amplitude of a sound wave.

12. Explain how the windows of a house may be broken by an explosion several miles away.

148. Velocity of Sound. — The flash of a distant gun is seen before the report is heard. Lightning often dazzles us several seconds before the crash of thunder reaches our ears. The puff of steam issuing from a locomotive whistle may be seen an appreciable interval before the sound reaches us. In all these cases, the light waves and the sound waves start at the same instant from the vibrating body. The speed of light, however, is so great that we can neglect it in finding the rate at which sound travels through the air. The distance of the gun from the observer divided by the time between the flash and the report gives the approximate velocity of sound per second.

This was the method used in 1823 by Moll and Van Beek, two Dutch scientists. They placed a cannon on each of two hills about eleven miles apart. The two cannons were fired and the time between flash and report noted by the observer on each hill. The average of a number of observations showed that sound traveled about 1100 feet per second in air. Two cannons were used in the determinations so as to avoid any error due to the force of the wind.

Sound travels faster in warm air than in cold air. It has been found that the velocity *increases 2 feet per second for each degree* increase in temperature (Centigrade scale). Accurate determinations show that *the velocity of sound in air is 1090 feet per second at 0° C.*

The amount of water vapor in the air affects the velocity of sound, since water vapor is less dense than air. In hydrogen, the least dense of all gases, sound travels almost four times as fast as in air. For any one gas, however, variations in density do not affect the velocity of sound provided the temperature is the same. Thus, at a given temperature, sound travels as fast through air at sea level as on a mountain top where the air is rarer.

The velocity of sound in fresh water was determined in 1827 at Lake Geneva by two scientists who stationed two vessels about eight miles apart. From each vessel they suspended a bell so that it would be under water. Their method of observation was like that of the cannon experiment and gave a result of 1435 meters (4708 feet) per second as the velocity of sound in water.

Out of this experiment grew submarine signaling, a very reliable method of communication between lightships and vessels nearing land, and between vessels approaching each other, particularly in a dense fog. Part of the vessel acts as a sounding board and the signals are sent or received by delicate apparatus. During the World War, the submarine warfare developed to a marked degree the accurate locating of vessels by means of devices that detected the sound waves passing through the water.

The variation of the velocity of sound with different solids emphasizes the principle that the rate at which sound waves travel depends upon the elasticity of the medium. In lead,

the velocity at 0° C is 1420 meters per second; in pine wood, 3300 meters; in glass, 4860 meters; and in steel, 4975 meters.

149. Velocity and Wave Length. — Sound has been found to travel 1090 feet per second. If a fork gives 256 vibrations per second, at the end of a second the first wave will be 1090 feet away. Between the fork and the first condensation there will be 255 other condensations. In this case, the length of each wave will be $\frac{1}{256}$ of 1090 feet. The length of any sound wave may be found in the same way if the velocity and frequency are known. Therefore:

$$\textbf{Wave length} = \frac{\textbf{velocity}}{\textbf{frequency}}.$$

From this relation, it will be seen that the velocity will be equal to the product of the wave length and the frequency.

WAVE LENGTHS IN AIR

Source of Sound	Frequency	Wave Length in Air at 20° C
Lowest organ note	16	70.7 ft.
Lowest piano note	27	40.3 "
Low C of bass voice	65	17.4 "
Middle C	256	4.4 "
High C in soprano voice	1024	1.1 "
Highest piano note	3500	.324 "

150. Echoes. — We are all familiar with the fact that light can strike a mirror and return to us so that we see an image in the glass. Sound waves as well as light waves can be reflected and the *reflections of sound are known as echoes.* These repetitions of sound return to us from the faces of cliffs (Figure 222), from high river banks, from walls, and

from the edge of a forest. The condition for an echo is a surface large in comparison with the length of the sound wave. The angle at which a sound wave strikes a surface so as to be reflected is known as the *angle of incidence;* the angle at which the sound bounds off from the surface is known as the *angle of reflection.* Measurements, particularly with

FIGURE 222. — AN ECHO VALLEY IN UTAH.

The words of a speaker standing in the notch of rocks at the left are echoed with startling distinctness by the cliff at the right.

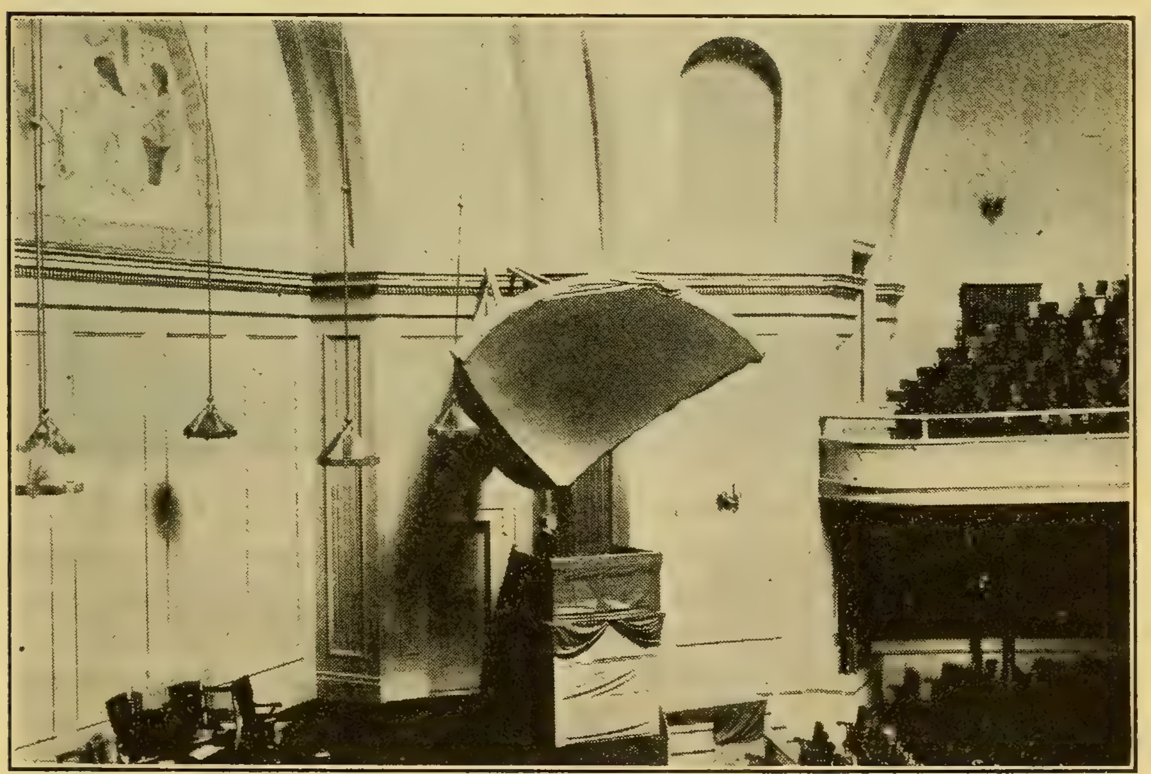
very short waves, show that the angle of incidence is equal to the angle of reflection.

Unless successive sounds are $\frac{1}{10}$ of a second apart, the ear cannot distinguish them as distinct sounds. Inasmuch as sound travels about 110 feet in this tenth of a second, a wall must be over 55 feet away to give an echo. In the ordinary room the nearness of the walls enables the sound reflection or echo to return to the ear in time to reënforce the original sound. Outdoors the sound of the voice is not usually so reënforced and it is harder to hear.

In an auditorium, the reflected sound waves from the walls and ceiling may return at such intervals as to overlap the words of the speaker to the confusion of his listeners (Figure 223). To reduce such reverberations, loose cloths are sometimes hung from the walls or the walls are padded with loose material. In whispering galleries such as that in the dome of the Capitol at Washington, a whisper may be heard very distinctly at a point some distance away. In such cases, the spherical or

Courtesy of University of Illinois Experiment Station and of Professor F. R. Watson.

FIGURE 223. — Section showing reflection of sound waves in the auditorium of the University of Illinois.



Courtesy of University of Illinois Experiment Station and of Professor F. R. Watson.

FIGURE 224 — REFLECTOR IN THE UNIVERSITY OF ILLINOIS AUDITORIUM.

This reflects sound waves forward. Draperies hung at the rear of the room prevent all echoes.

ellipsoidal shape of the dome is responsible for the curious effect, making the whisper focus at a definite point. A wall built in the shape of a concave reflector often forms the back of a bandstand to reflect the sound forward to the audience. Similar reflectors are sometimes placed back of a pulpit (Figure 224).

Sound projected between two parallel walls may be reflected a number of times so as to produce *multiple echoes.*

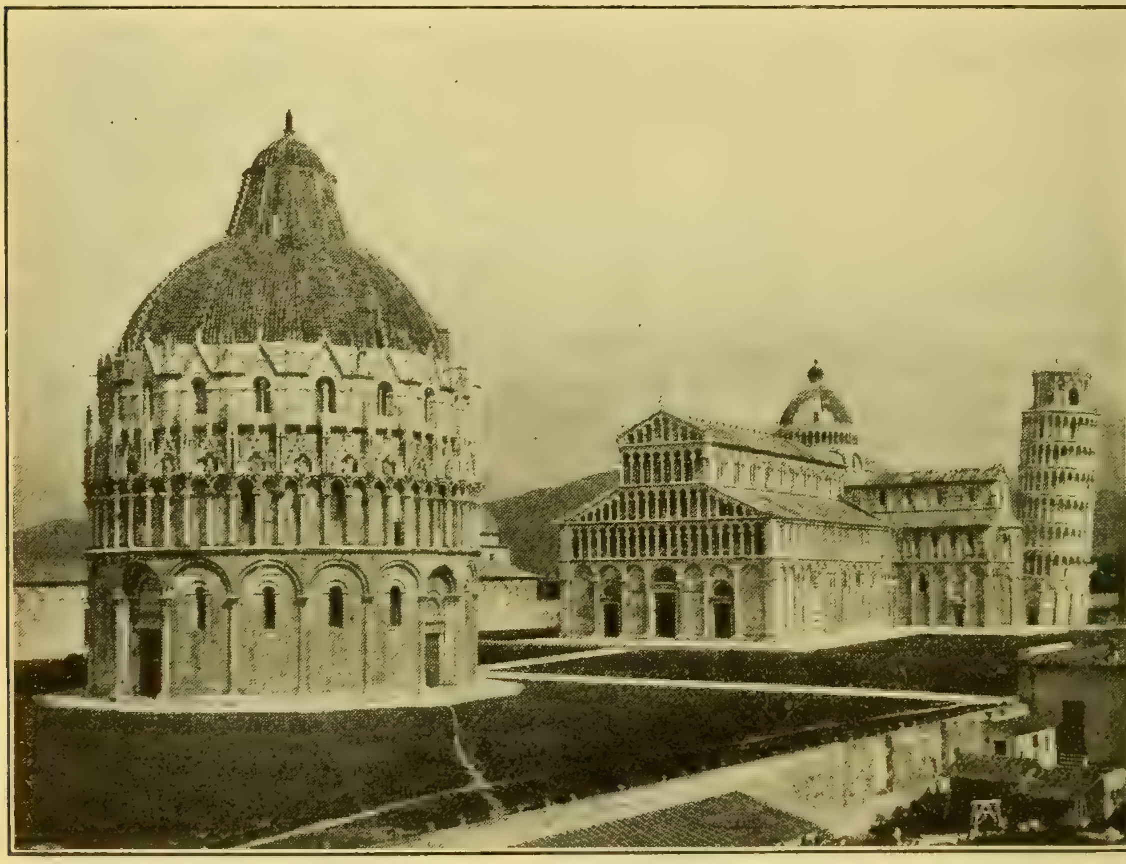


FIGURE 225.—THE BAPTISTRY OF PISA.

When the guide sings several notes, the echoes combine and for many seconds a sound like an organ chord persists. In the Cathedral beyond hangs the lamp that suggested the pendulum to Galileo and from the Leaning Tower in the background he made his famous experiment on falling bodies.

The Baptistry in Pisa (Figure 225) is famous for prolonging musical notes for many seconds in this way. The roll of thunder is due to multiple echoes between clouds or between clouds and the earth.

Reflection of sound takes place whenever a sound wave enters a medium of different density or elasticity. Part of the energy of sound waves is lost by reflection when passing through air regions of different densities. Sound, then, is best transmitted on days when the atmosphere does not vary in character from one place to another. On damp or foggy days, the air is most likely to be the same throughout. On these days sound can be heard for long distances.

151. Musical Sounds. — The slamming of a door, the crash of an object on the floor, and the clapping of hands produce disturbances that have no regularity of vibration and to which we can assign no pitch. Such sounds are called *noises,* and are disagreeable to the ear because of lack of rhythm. When the motor of an automobile begins to turn, we hear a noise, but when the car is running, a hum is produced that is somewhat musical. A *musical sound* arises from a source of regular vibration.

Every musical sound has three identifying properties or *characteristics,* which distinguish it from all other sounds, just as a child's height, weight, and coloring distinguish it from others. These three characteristics are *pitch, loudness or intensity,* and *quality.*

152. Pitch. — By *pitch* is meant the highness or lowness of a tone. Pitch depends upon the number of waves per second produced by the vibrating body, and so upon the length of the sound waves. This can be shown experimentally by the use of Savart's wheel (Figure 226). This is a brass wheel with projecting teeth equally distributed on its circumference and mounted so that it can be rotated at various speeds.

Experiment 62. — Hold a card against the teeth of a Savart's wheel and turn it slowly so that you hear the vibrations of the card as dis-

tinct sounds. Increase the speed a little. *Is the sound musical?* Rotate the wheel rapidly but at a uniform rate. *Does the musical sound produced have a low or a high tone (pitch)?* Increase still more the speed of rotation. *How is the pitch of the sound affected? How does the speed affect the number of vibrations? State the relation between the pitch and the number of vibrations (frequency).*

The more rapidly the wheel is rotated the greater is the number of vibrations of the card. These produce air dis-

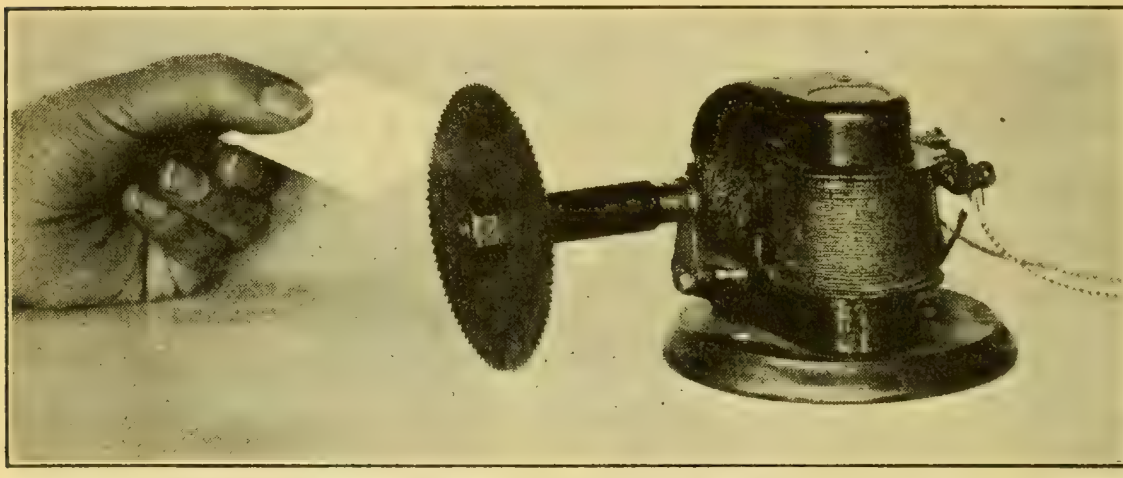


FIGURE 226. — SAVART'S WHEEL.

The vibrating card produces a high-pitched musical sound.

placements which travel to the ear as a musical note, provided there are a sufficient number of them per second and that they come at a uniform rate. *The pitch of the note depends upon the frequency of the vibrations.*

The siren is another device for demonstrating that the pitch depends upon the frequency of vibration. The simple form (Figure 227) consists of a circular disk mounted on a central axis that can be rotated rapidly. The outer circles of holes on the disk are evenly spaced and the inmost circle unevenly. A rubber hose from a bellows or blower directs a narrow stream of air on the disk. As a hole passes the hose, a puff of air shoots out through the hole.

EXPERIMENT 63. — Rotate the disk of a siren and direct the current of air against the inmost circle of holes. *Does the succession of puffs from the unevenly spaced holes produce a musical note?* Repeat with the next circle of holes, and then with the outer ones. *Which of the two outer circles of holes will give the more rapid succession of puffs? Why? Which produces a musical note of the higher pitch? State the relation between the frequency of vibration and the pitch.*

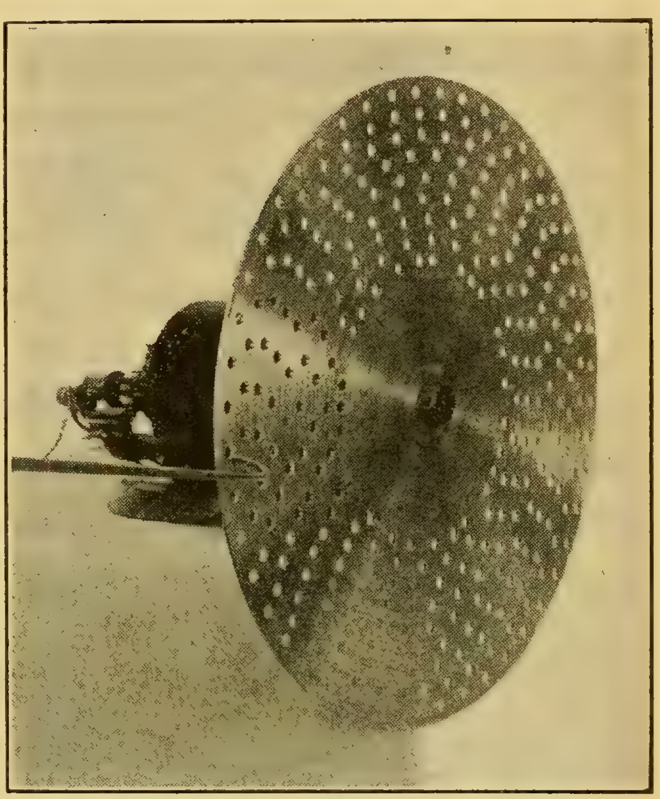


FIGURE 227. — SIMPLE SIREN DISK.

The blowpipe at the left directs the air in puffs through the holes when the disk is rotating. These puffs produce sound waves.

The frequency of vibration depends upon the number of holes that pass the air jet in each second. Multiplying the number of holes in a circle on the disk by the number of revolutions that it makes per second gives the vibration frequency.

The siren has many forms, some complicated, but the basic principle of all is the forcing of air or steam through the holes of a rapidly rotating disk. Sirens are used for sounding fire alarms, for fog signals, and for warning signals on fire apparatus. For such uses, several high-pitched notes are combined into a very characteristic sound of warning, or a single note of variable pitch is sounded.

The lowest musical sound that the ear can detect has 16 vibrations per second; the highest, a vibration frequency of nearly 40,000. Many persons, however, fail to hear notes of such high pitch and even those that are much lower.

Their ears fail to respond to vibrations of such short wave lengths. Cases are related of persons of good hearing who cannot hear the chirp of a sparrow or the shrill note of a cricket. It is believed that certain small insects emit notes of too high frequency for any human ear to detect. Aging persons gradually lose their ability to hear notes of high pitch.

A common observation is the almost terrifying shriek of a locomotive whistle on a rapidly approaching train. This is due to the source of the sound rapidly approaching the ear. This results in the ear receiving from the source a much greater number of sound waves per second and the pitch appears to be raised. When the source of sound retreats from the ear, relatively fewer sound waves reach the ear per second and the pitch appears to lower. This effect is known from its discoverer as the Doppler effect.

QUESTIONS

1. Describe how the velocity of sound was determined by two Dutch scientists.

2. What is the velocity of sound in air at 0° C? What is the rate of increase for each rise of temperature of 1°? What would be the velocity at 20° C?

3. How is the velocity of sound in air affected by (*a*) the presence of water vapor; (*b*) the altitude?

4. Compare the velocity of sound in air with the velocity in (*a*) hydrogen; (*b*) water; (*c*) pine wood.

5. A clap of thunder was heard 12 seconds after the corresponding lightning flash. How far away was the lightning?

6. Give the principle of submarine signaling. How is it useful?

7. What are echoes? How is an echo produced?

8. An echo is heard from a cliff in 2 seconds. If the temperature is 25° C, how far away is the cliff?

9. The pilot on a steamer blows a whistle and 8 seconds later hears an echo from a distant iceberg. How far away is the iceberg?

10. How far away must a wall be in order to give a distinct echo?

11. Why is it necessary to control the reflection of sound in auditoriums? How is it done?

12. Distinguish between a noise and a musical sound.

13. What are the three characteristics of a musical sound?

14. What changes in sound *waves* affect (*a*) the pitch; (*b*) the loudness or intensity; and (*c*) the quality of a musical sound?

15. Describe an experiment which shows that the pitch of a sound depends upon the frequency of vibration.

16. Name some practical uses of sirens. What makes them effective for these purposes?

17. How is the Doppler effect produced? Give some examples of it.

153. Loudness or Intensity. — The harder we strike an anvil with a hammer or the more sharply we strike the prong of a tuning fork on a table, the louder the sound. Loudness, then, depends upon the energy of the initial disturbance. This energy is gradually scattered, since the sound travels away through the air in all directions. At a distance a loud sound may have dwindled away to a faint one. In general, it may be stated that the intensity of a sound is inversely proportional to the square of the distance from its source. This is not quite exact, since there is always a certain loss due to the internal friction of the air and to other causes.

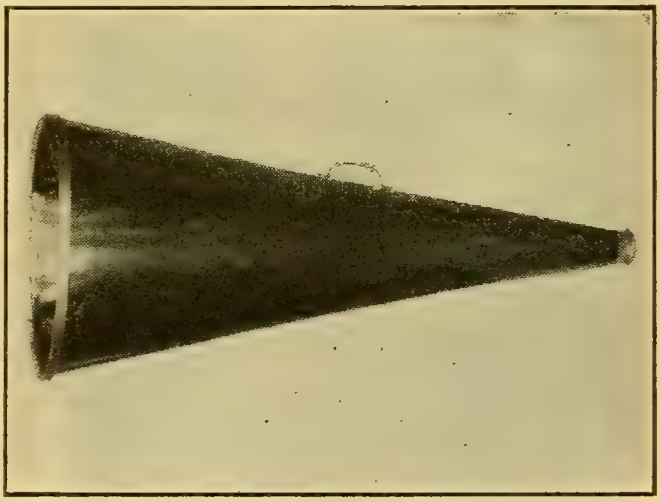


FIGURE 228. — MEGAPHONE.

The sound waves are prevented from spreading out.

In *speaking tubes*, the sound waves are not allowed to spread in all directions and the main loss in wave energy is

only that due to the friction along the walls of the tube. The voice of the captain in the pilot house is carried to the engine room with little loss in intensity. In the *megaphone* (Figure 228), the sound waves are directed along the axis of the instrument, so that a loud effect is produced at a distance from the speaker.

The loudness of a sound is determined by the amount of swing to the air particles as the sound wave passes. This amount of swing is the amplitude of the wave. *The loudness of sound depends on the amplitude of the sound wave.*

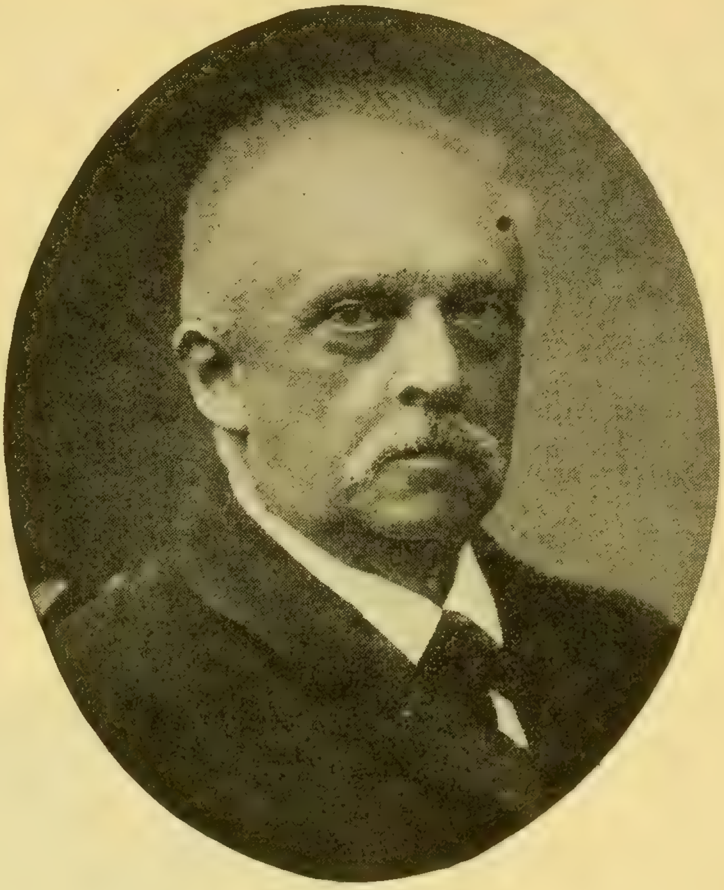
154. Sounding Boards. — In stringed instruments, increased loudness is secured by the use of sounding boards, without which such instruments would be inaudible at any considerable distance.

Figure 229. — A Door Panel Makes an Excellent Sounding Board.

Experiment 64. — Strike the prong of a tuning fork sharply on a piece of rubber tubing. Note the loudness of the sound. Place the vibrating fork on a sounding board (Figure 229). *What effect is there on the loudness of the sound?*

Experiment 65. — Pluck a tightly stretched string. Note the loudness of the sound. Attach the string so that it can vibrate over a sounding board. Pluck the string and decide how the sounding board affects the loudness of the tone produced by the vibrating string.

The sounding board was set into vibration by the tuning fork in the first experiment, and by the string in the second experiment. Such vibrations are called "forced vibra-



Hermann Ludwig Ferdinand von Helmholtz (1821–1894) explored nearly the whole range of the science of his time and made important contributions to almost every branch of scientific knowledge. It is difficult to place any one of his efforts above the others. He investigated the eye as an optical instrument and invented an instrument for measuring its curvature and determining its defects. He explained the quality of sound as being the result of overtones. He advanced theories as to the mechanism of hearing and of color vision. He credited the idea of conservation of energy to Mayer, but explained and stated the law. His name is also associated with the theory of electro-dynamics which Maxwell expanded and Hertz proved.

tions." The sounding board has not a fixed vibration frequency, but will vibrate in unison with any body forcing vibrations upon it. The vibration of the sounding board, added to the effect produced by the fork or string alone, makes the sound louder. The sounding board increases the area of vibrating surface, so that the air that might have slipped by the string is set in vibration.

A sounding board set in vibration by a fork or string, gives out a louder sound than either the fork or string alone.

155. Quality of Sound. — The musical sounds from the piano, the organ, the violin, and the flute, are all agreeable to the ear. These instruments, however, when sounding the same note, produce sounds so differing in *quality* that we may distinguish each instrument from the others. The sound of the human voice differs in quality with individuals and even with nationalities. One cannot understand the reasons for differences in quality unless he realizes that musical sounds do not usually result from simple vibrations, but from a blending of vibrations that modifies the form of the sound wave issuing from the musical instrument.

156. Nodes and Segments. — When a string of a musical instrument is plucked so that the string is made to vibrate as a whole, the production of the musical note is easily understood. When, however, a bow is drawn across the string at the proper point, the string may not only vibrate as a whole, but in parts as well. This complicated process makes the musical note harder to explain, but without such complications musical instruments would be unable to give many of their richest tones. Several experiments easy to understand make the complications seem much simpler.

Experiment 66. — Attach one end of a long coiled spring (a rope or a long rubber tube may be used) to the wall. Holding the free end

with the hand, make the spring describe a loop like that made by a child in skipping a rope. *Are all parts of the spring between the hand and the fixed end in motion?* Make the spring vibrate in two loops or *segments. Where on the spring is there a point of no vibration (a node)? How many segments are in vibration? Can the spring be considered to be vibrating as a whole and in segments at the same time?*

One end of a rope may be tied to a tree and the rope made to describe a single loop, as shown in Figure 230. Between the two fixed ends, the rope vibrates as a whole. With a little practice the rope may be made in loops or segments (Figure 231). The two segments join at points in the rope where there is no vibration. Such a point is called a *node*. There is also a node at the attached end and at the hand. The parts of the rope between nodes are *segments*.

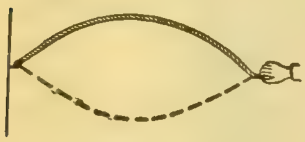


FIGURE 230.

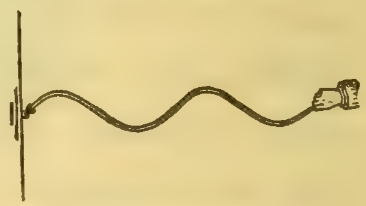


FIGURE 231.

157. Fundamentals and Overtones. — A sonometer (Figure 232) is simply a wire stretched above a long wooden box with a device for tightening the wire.

EXPERIMENT 67. — Pluck the string of a sonometer and note the pitch of the sound. *How is the wire vibrating?* The tone produced is the *fundamental* of the wire. Touch the wire lightly with a finger midway between the two fixed ends. Pluck the wire. *In how many segments is the wire vibrating?* This note is an *overtone. Compare the pitch of the overtone with the pitch when the wire vibrates as a whole (fundamental).*

Stop the vibration of the wire with the finger at one third of its length. Pluck this third of the wire. *Compare the pitch of this second overtone with the pitch of the fundamental and with the pitch of the first overtone.*

When the string of a sonometer vibrates as a whole, it produces its lowest tone or *fundamental* (Figure 233). When it vibrates in two segments, it produces its *first overtone.* This is one octave higher in pitch than the fundamental. When the string vibrates in thirds, the second overtone

results. Still higher overtones or harmonics can be obtained when the string vibrates in a greater number of segments. A string of a musical instrument can be vibrating as a whole and at the same time be vibrating in segments. In other words, the string may be giving out its fundamen-

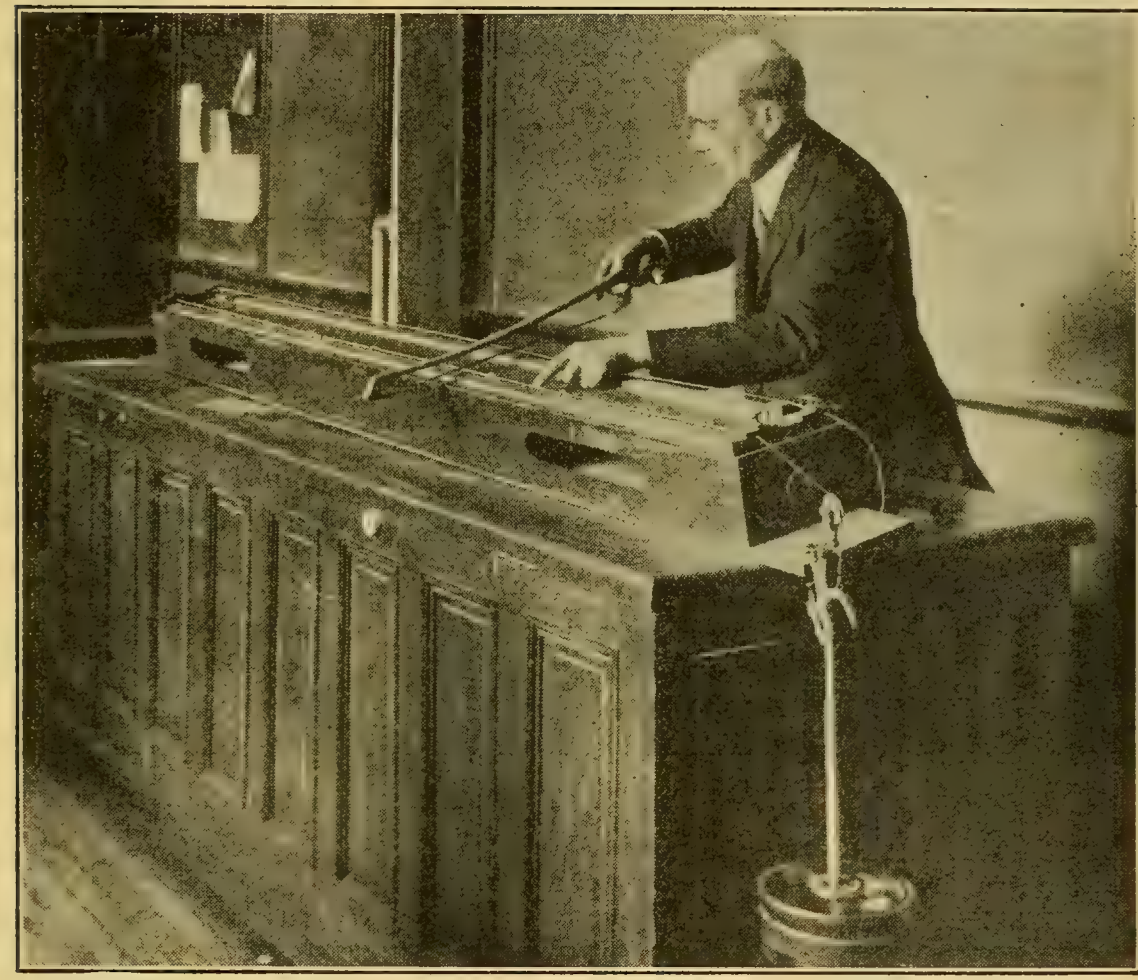


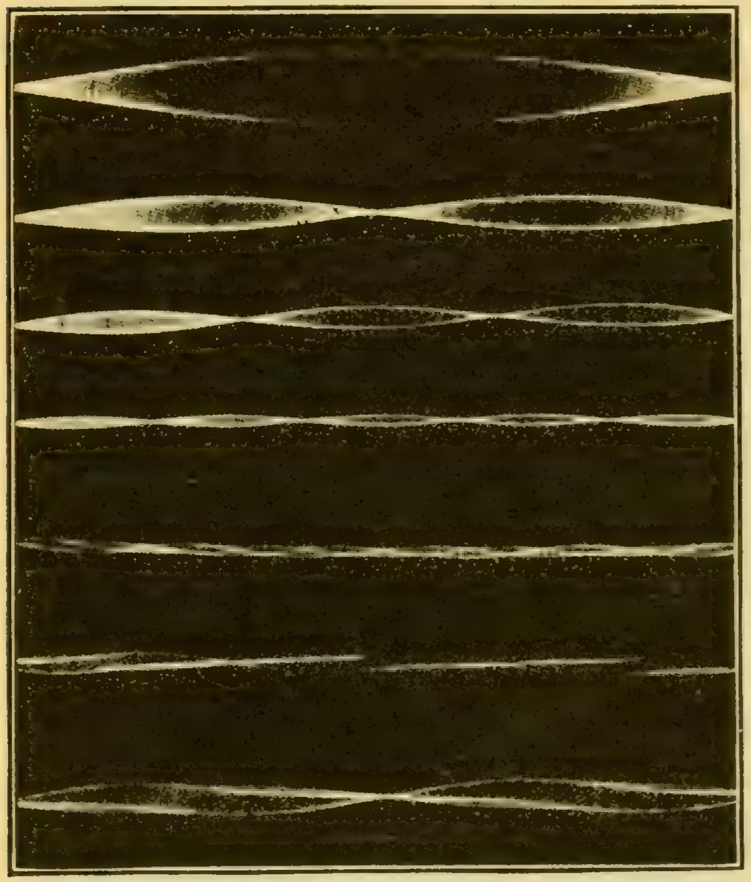
FIGURE 232. — SONOMETER IN USE TO SHOW OVERTONES.

It is being touched to form a node and paper rings are in place to show the location of other nodes when the string is bowed.

tal and a number of overtones at the same moment. This combination is responsible for the quality of the tone.

The quality of a sound depends upon the number and relative strength of the overtones that are united with the fundamental. The particular combination of overtones effected determines the *form* of the sound wave.

An interesting experiment with the sonometer to show nodes and vibrating segments can be made with small paper rings slit along a radius (Figure 234). These paper riders are placed along the sonometer wire which is then made to vibrate by drawing a bow across it when the finger is at an even fractional part of its length (Figure 232). The riders will hold their positions at the nodes, but will dance violently at the middle of the segments.



Courtesy Harcourt, Brace and Co.

FIGURE 233. — PHOTOGRAPHS OF VIBRATING STRINGS MADE BY PROF. D. C. MILLER.

The string is shown vibrating as a whole and in 2, 3, and 5 segments. The three bottom pictures show it vibrating to give fundamental and overtones at the same time.

When the finger is at one fourth of the length, nodes are found at one half and three fourths. When the finger is at one fifth of the length, the nodes are found at the other fifths; and so on. Since the point at which the string is plucked or bowed cannot be a node, the number of overtones depends upon the place where the string is plucked or bowed. Piano strings are struck near one end in order to produce a certain number of overtones. The felt hammers of old pianos are

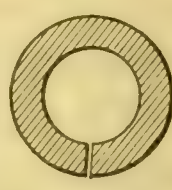


FIGURE 234.

sometimes so hardened that discordant overtones are produced when the felt hammers hit the strings. A sound of *unpleasant quality* results.

QUESTIONS

1. (*a*) Name three things that determine the loudness of a sound. (*b*) Why does the ringing of a distant church bell sound faint?

2. How do speaking tubes affect sound waves?

3. To what is the difference in quality of musical sounds due?

4. Explain how a sound board affects the loudness of the sound from a vibrating fork or string.

5. Describe an experiment with a rope that illustrates the meaning of *nodes* and *segments.*

6. What is a sonometer?

7. What is the *fundamental* of a vibrating string? What is an *overtone?*

8. Compare with each other the pitch of the fundamental, the first overtone, and the second overtone.

9. Describe an experiment by which you can modify the form of a sound wave.

10. Upon what does the quality of a sound depend?

SUMMARY

Sounds arise from the vibrations of bodies. The vibration **frequency** of a body is the number of vibrations that it makes in one second.

Sounds are **transmitted** by elastic media, whether these are solids, liquids, or gases. Sound is transmitted in straight lines in all directions from its source.

Waves transmit vibrations of many kinds. **Transverse waves** consist of a crest and a trough. The **length** of a transverse wave is the distance from one crest to the next, or from one trough to the next. The **amplitude** of a transverse wave is one half the vertical distance from crest to trough. Water waves are transverse waves.

Longitudinal or compression waves consist of a condensation and a rarefaction. A **condensation** is a crowding together and a **rarefaction** is a spreading apart of the particles transmitting the wave. **Sound waves** are longitudinal or compressional waves. The vibrations of a sounding body set up a series of sound waves that travel to the ear and produce the sensation of sound.

The **length** of a sound wave is the distance from one condensation to the next. The **amplitude** is the distance that a single particle is displaced during the passage of a sound wave.

The **velocity** of sound in air is 1090 feet per second at 0° C. The velocity in air increases 2 feet per second for each degree increase in the Centigrade temperature. The velocity of sound in fresh water is 4708 feet per second.

$$\textbf{Wave length} = \frac{\textbf{velocity of sound}}{\textbf{frequency}}$$

Echoes are reflections of sound. Reflection of sound takes place whenever a sound wave strikes a medium of different elasticity.

A **musical sound** is caused by regular vibrations; a **noise** by uneven vibrations.

The three characteristics of a musical sound are pitch, loudness, and quality. **Pitch** depends on the **frequency** of the waves; **loudness** on the **amplitude** of the waves; **quality** on the **form** of the waves.

The greater the frequency, the higher the pitch. This can be shown by the siren. The ear can distinguish as musical sounds pitches ranging from 16 vibrations to many thousand vibrations per second.

The **energy** used in producing a wave determines the **amplitude** of the wave and hence the **loudness**. Amplitude and loudness **decrease with distance** from the source of sound. Sounds are also made louder by the use of sounding boards, reflectors, megaphones, and speaking tubes.

Quality distinguishes one musical instrument from another, and

one voice from another of the same pitch. It is determined by the number and intensity of the **overtones** produced by the vibrations of the segments of the sounding body.

The **fundamental** (lowest) tone is produced by a sounding body vibrating as a whole. If there are points in the body, called **nodes**, at which the vibration is very small, the **segments** between these nodes emit overtones. Many of the simpler overtones are called **harmonics**, because they make agreeable combinations with the fundamental and with each other, and produce sounds of pleasing quality.

EXERCISES

1. Why is it that the clapping of your hands makes a noise and the waving of your arms does not?

2. How is it sometimes possible for imprisoned miners to signal the approaching rescuers?

3. What kind of waves are water waves? Describe the motion of a water particle in a wave of the ocean.

4. Mention one factor that affects the length of a sound wave. Mention three factors that affect its amplitude.

5. Describe the action of the air particles in transmitting the vibrations of a tuning fork to the ear.

6. When the flash of a gun is seen 3 seconds before the report is heard, how far is the gun from the observer, the temperature being 25° C?

7. How long would it take sound to travel 12.5 miles at 15° C?

8. A man sets his watch at noon by the sound of a factory whistle 3 miles away. If the temperature of the air is 20° C, how many seconds slow will his watch be by the time at the factory?

9. State and solve a problem involving an echo and the velocity of sound.

10. Explain (*a*) whispering galleries; (*b*) multiple echoes.

11. Why does the pitch of a buzz saw fall as it enters a board?

12. How does increasing the speed of rotation of a phonograph record change the character of the music produced?

13. Why does the sound of an automobile horn seem sharper as it approaches you?

14. Account for the hum of a bullet.

15. How does an ear trumpet aid a person with defective hearing?

16. Explain how a megaphone helps a cheer leader at a football game.

17. What are the "forced vibrations" of a sounding board?

18. Distinguish between (*a*) *fundamental* and *overtone;* (*b*) *node* and *segment.*

19. Compare the vibration of a string plucked near one end with its vibration when plucked at the middle. Compare the tones produced.

20. What is an *overtone?* How are overtones produced? What effect do they have on the sound produced by a string?

21. Explain why a tremendous noise produced on the moon could not be heard on the earth.

22. Describe the motion of (*a*) a body which is producing a sound; (*b*) an air particle transmitting the sound; and (*c*) an eardrum that is receiving the sound.

CHAPTER XIII

STRINGS AND AIR COLUMNS IN MUSIC

158. Laws of Vibrating Strings. — No form of music is more appreciated than that produced by stringed instruments. In the tuning of a violin, the strings are tightened by putting more pull or tension upon them. In playing the

FIGURE 235. — STUYVESANT HIGH SCHOOL ORCHESTRA.

Violins in the foreground and bass viols in the rear apply the laws of strings; the wind instruments use vibrating air columns.

instrument, the vibrating lengths of the strings are changed by rapid movements of the fingers. The violinist by his skill can produce a wide range of effects, but all of them are

in accordance with the laws of vibrating strings. The first of these laws deals with the length of strings, and can be illustrated by experiment.

EXPERIMENT 68. — Arrange a sonometer as shown in Figure 236, placing the bridge, *B*, about 3 feet from the right end. Add enough

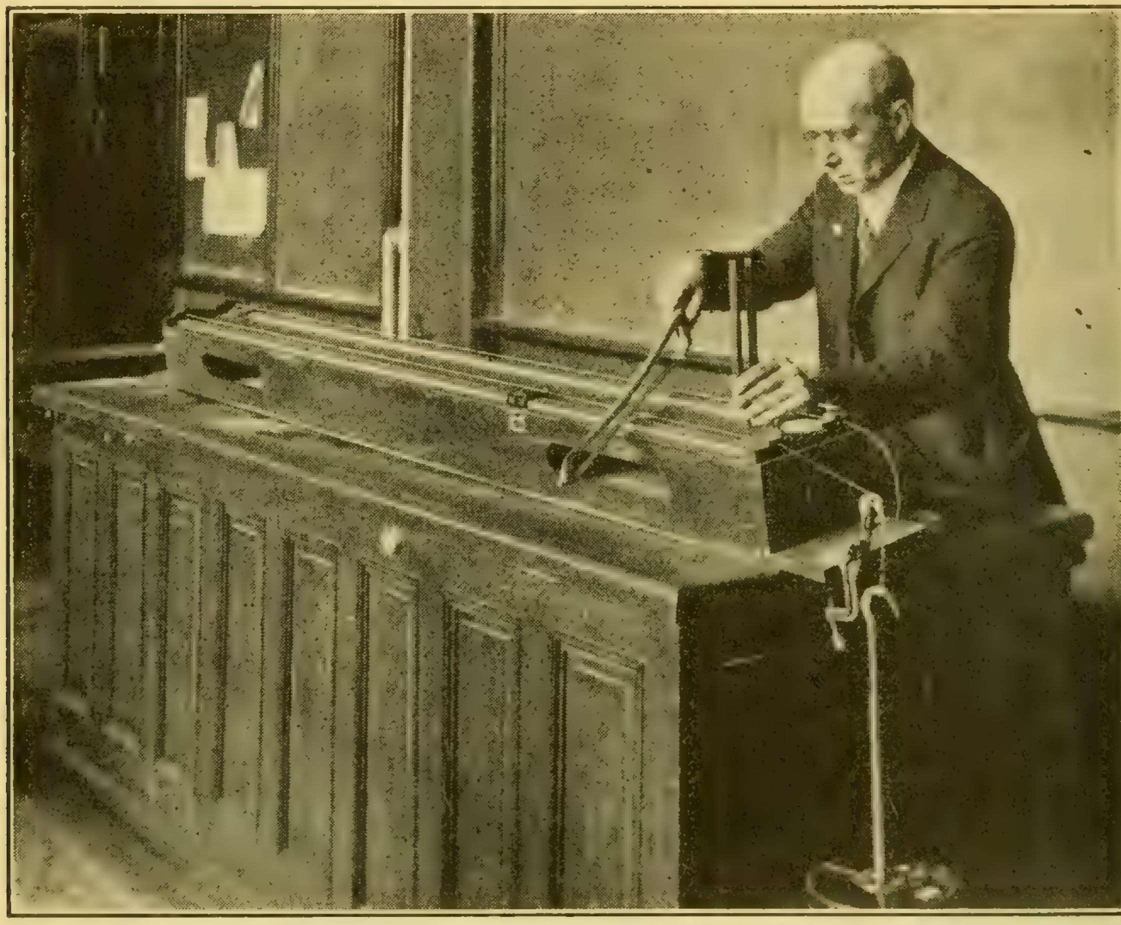


FIGURE 236. — SONOMETER FOR STUDYING LAWS OF STRINGS.

The string under test is stretched over fixed bridges at the ends by weights placed on the hanger at the right. The second string may be used to compare the effect of mass. *B* is a movable bridge.

weight to stretch the string tight enough to give a clear note when it is plucked. Set the string into vibration by plucking it. Then strike a C′ tuning fork (frequency 256) on a flat cork or piece of pressure tubing. If the wire and the fork give sounds of the same pitch, you will not hear any alternate loudness and faintness of the sound. If the sounds are not in unison, increase the tension by adding more weight till unison is obtained, shifting the bridge a little if necessary. *What length of string gives 256 vibrations per second?*

Move the bridge until the string is one half of the original length. Compare the note made by plucking it with that of a C″ fork (frequency 512). *What length of string has this frequency? Compare its length with a string vibrating 256. State the general relation between the number of vibrations per second and the length of the string.*

The preceding experiment shows that a string 18 inches long makes twice as many vibrations per second as one 36 inches long, provided it has the same tension and the same mass per unit length. *The number of vibrations of a string, then, is inversely proportional to the length of the string.* This is the *law of length.* The *law of tension* can be shown with the same apparatus.

EXPERIMENT 69. — *What weight gave the tension on the wire when its frequency was 512?* Keeping the vibrating wire the same length, gradually decrease the tension by removing portions of the weight. *How does the decrease in tension affect the pitch?*

If desired, reduce the weight to one fourth of its original value and compare the pitch of the wire with that of a C′ fork. *What tension gives this frequency? What is the ratio of the square roots of the two tensions? What else has the same ratio when the length of the vibrating string is kept constant?*

When a vibrating string is kept at the same length and its tension is increased, the pitch becomes higher. Thus in the tuning of a stringed instrument, the player brings a string up to pitch by tightening it with a thumb screw. In the experiment just given, it was shown that *the vibration frequency of a string is directly proportional to the square root of its tension.* This is the *law of tension.*

Makers of musical instruments know that strings of different diameters, although of the same length and under the same tension, differ in their vibration frequency. With strings of the same material, differences in diameter mean differences in the mass per unit length. The greater the

mass per unit length, the lower the pitch, a fact which is well illustrated by the heavy strings of a piano. This third law of strings stated more exactly is: *The vibration frequency of a string is inversely proportional to the square root of its mass per unit length.*

The three laws of vibrating strings may be best remembered by the following statement. The vibration frequency of a string is:

1. Inversely proportional to its length;
2. Directly proportional to the square root of the tension;
3. Inversely proportional to the square root of its mass per unit length.

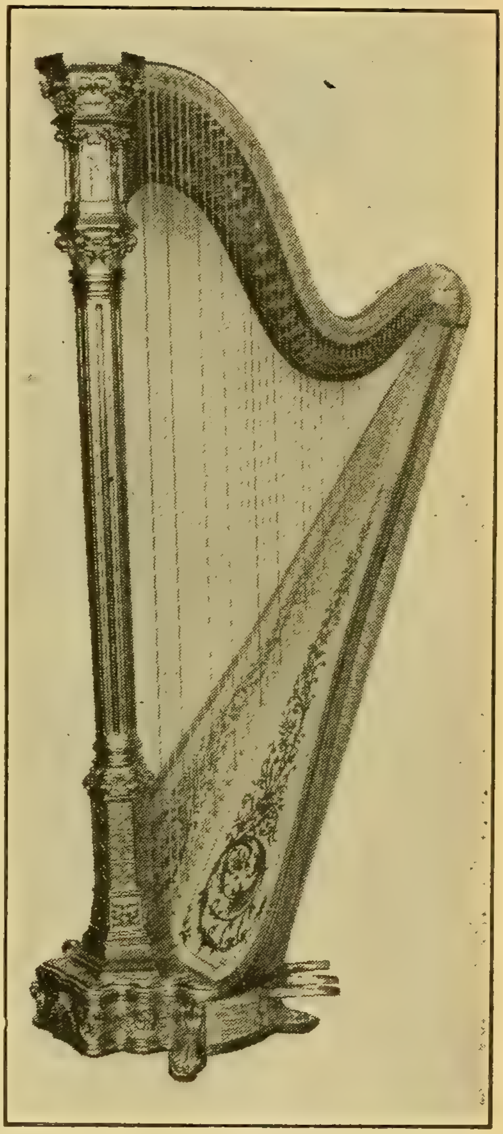
Courtesy Oliver Ditson Co.

FIGURE 237. — MANDOLIN AND VIOLIN.

Strings of different size are used; the pegs vary the tension to tune the strings. The mandolin has "frets" to guide the fingers in stopping the strings.

159. Stringed Instruments. — In instruments like the violin, mandolin (Figure 237), guitar, banjo, and ukelele, a wide range of notes is produced with a few strings by "stopping" or shortening the vibrating length of the string with the finger. The triangular shape of a grand piano and of a harp (Figure 238) shows the application of the law of lengths by using longer strings for lower pitches. When greater length of string would be inconvenient, the mass of the string is increased by making it thicker or by winding it

with wire. The smaller stringed instruments also use strings of different mass. The tuning of all stringed instruments is accomplished by adjusting the tension. On the piano, *low* notes are produced by *long, loose, large* strings; *shrill* notes by *short, stretched, small* strings.



Courtesy Oliver Ditson Co.

FIGURE 238. — HARP.

Strings of different length and mass produce the notes. At the right is a large sounding board.

QUESTIONS

1. State three ways by which a violinist may play different notes of the scale.

2. How does pitch change as the length of a vibrating string changes?

3. A string 30 inches long makes 384 vibrations per second. How many v.p.s. does it make when shortened to 25 inches?

4. A cello string 35 inches in length makes 500 v.p.s. How many v.p.s. will a 28-inch portion of the string make?

5. In tuning a piano, does tightening the string raise or lower the pitch?

6. Two similar strings are stretched, one with 25 lbs, the other with 49 lbs. What is the ratio of their vibration frequency?

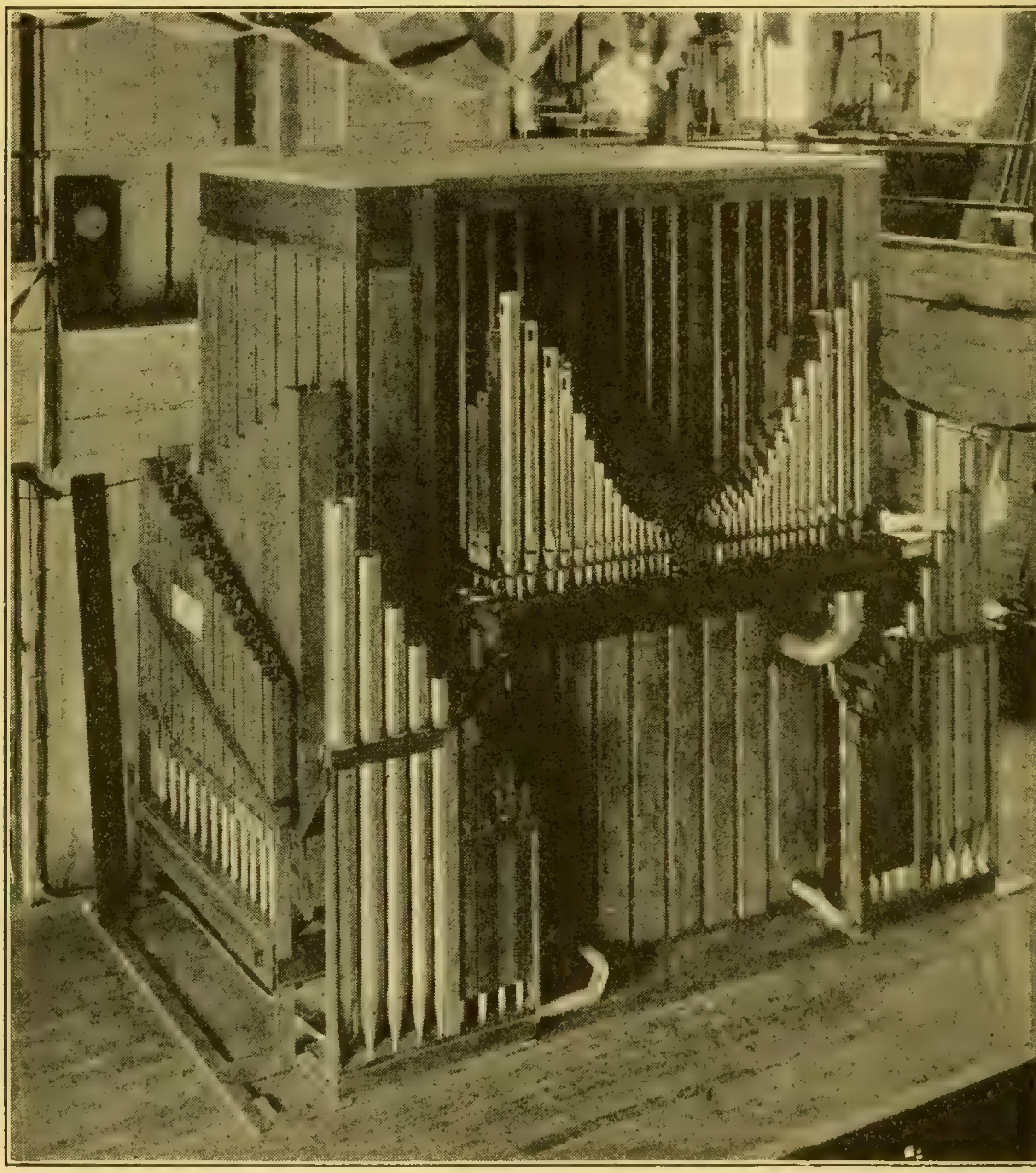
7. State the law of tension of vibrating strings.

8. Why are the strings of a cello and of a bass viol heavier than the strings of a violin?

9. Which strings of a piano are wound with coils of copper wire? Why?

10. Give the law relating the vibration frequency of a string with its mass per unit of length.

160. Open and Closed Pipes. — Boys blow into an empty cartridge shell to produce a shrill whistle. Likewise, organ



Courtesy Skinner Organ Co.

FIGURE 239. — A PIPE ORGAN ASSEMBLED READY FOR THE CASE.

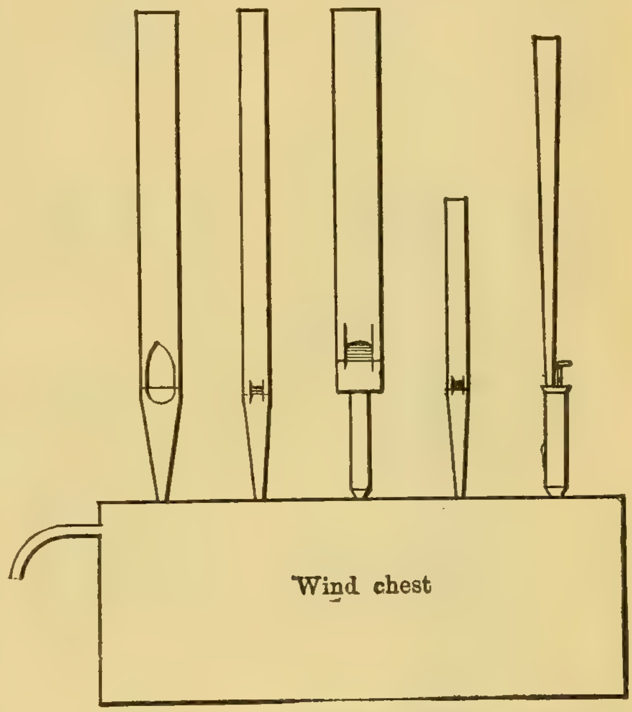
Many sets of pipes of different lengths and shapes are used to give different pitches and qualities. Each set is controlled by a "Stop." At the left end are seen a rank of closed wooden pipes and in front several ranks of open metal pipes. The space inside is nearly filled with pipes.

pipes give sound when air is blown into them because the air vibrates longitudinally in their tubes. In both open and closed organ pipes, air is blown in at the lower end of the tube.

The *open* pipe is also open at the top, while the *closed* pipe is closed at the top.

Experiment 70. — Blow into an open organ pipe and note the pitch of the sound. Blow into a shorter pipe. *Is the pitch higher or lower?* Repeat, using an open pipe longer than the first one. *Compare the pitch of the third pipe with that of the first. How does the pitch of an open pipe vary with its length?*

Air blown into an open organ pipe is set into vibration by striking a sharp edge. The length of the tube determines the length of the vibrating air column and hence the pitch of the sound. A short pipe gives a note of higher pitch (greater frequency) than a longer one (Figure 239). The size and shape of the tube also affects the pitch as well as the loudness and quality of the tone (Figure 240).



Courtesy Skinner Organ Co.

Figure 240. — Typical Organ Pipes.

A blower keeps the wind chest full through the tube at the left. When a key is pressed, a valve admits air to the proper pipe.

Experiment 71. — Arrange a series of eight glass tubes with the lower ends closed with corks, as shown in Figure 241. Blow a stream of air across the top of each tube. *How is the pitch (frequency of vibration) of the various tubes affected by the length of the air column?* By careful adjustment of the corks, the ordinary musical scale can be produced. The air in the glass tubes vibrates like air columns in closed organ pipes. *State the relation between the length of the air column in a closed pipe and the frequency of the note produced.*

In closed organ pipes the frequency of vibration varies inversely with the length of the air column.

EXPERIMENT 72. — Take a glass tube about a foot long that will give a musical note when blown across. Note the pitch of the tone produced when both ends are open. Close the lower end with the hand and blow again. *Compare the pitch of this closed pipe with the pitch of the open pipe of the same length.*

The fact shown in the last experiment by using a glass tube as both an open and as a closed pipe is equally true with regularly constructed organ pipes. A closed pipe gives a tone an octave lower than an open pipe of the same length.

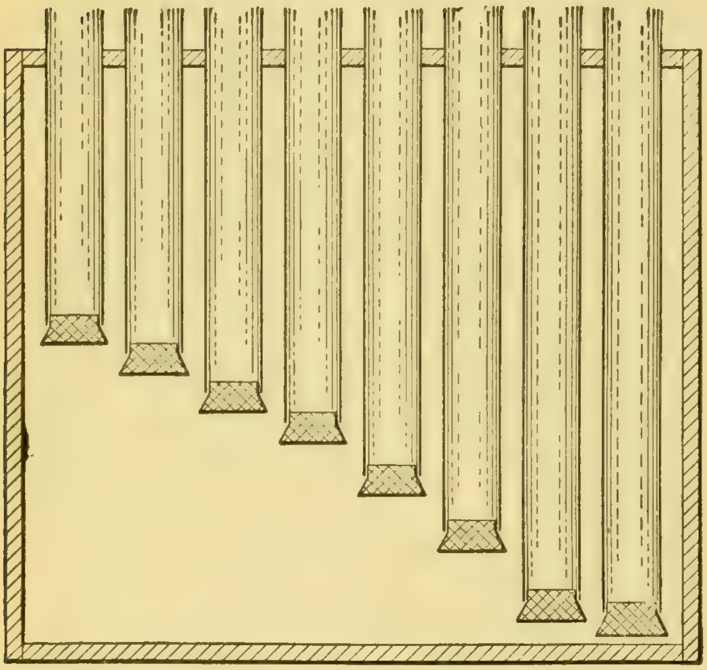


FIGURE 241. — SET OF GLASS PIPES TO GIVE THE NOTES OF THE SCALE.

The ancient Pipes of Pan were made like these from hollow reeds.

The nodes and antinodes in an open pipe can be located by using a pipe with a glass front and a diaphragm that can be moved up and down the tube (Figure 242). Fine sand placed on the diaphragm will be most violently agitated where the vibration is greatest, that is, at an antinode. A node is indicated where the sand is least disturbed. For the fundamental of an open pipe there will be found a node in the middle and an antinode at each end because at the ends the air is freest to vibrate. In a closed pipe, there is a node at the closed end and an antinode at the open end when the fundamental is produced.

It can be shown by experiment (§ 162) that the length of a closed pipe, that is, from node to antinode, is one quarter

the length of the sound wave made by it. Similarly, the length of an open pipe is one half the wave length when there is a node at the middle of the pipe and it is sounding the fundamental. These facts are shown diagrammatically in Figure 243 in which the distance between the curved lines indicates the relative amount of vibration. The fundamental of a closed pipe is a note whose wave length is four times as long as the pipe, while the fundamental of an open pipe has a wave length twice as long as the pipe.

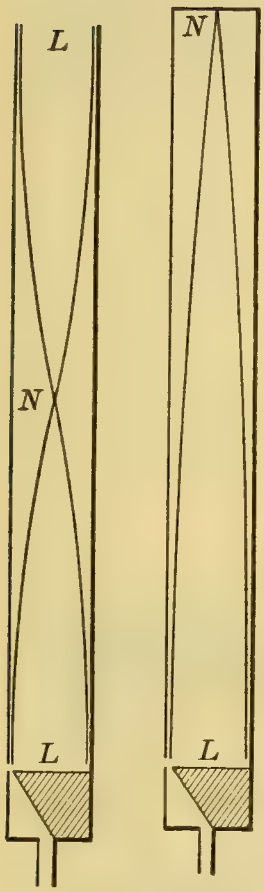


Figure 243. — Nodes, *N*; Antinodes, *L*, in Open and Closed Pipes.

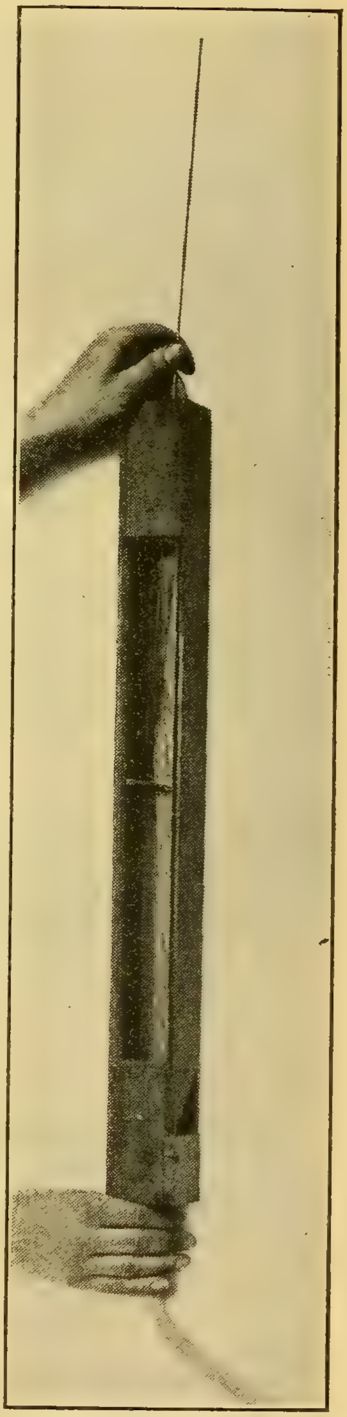
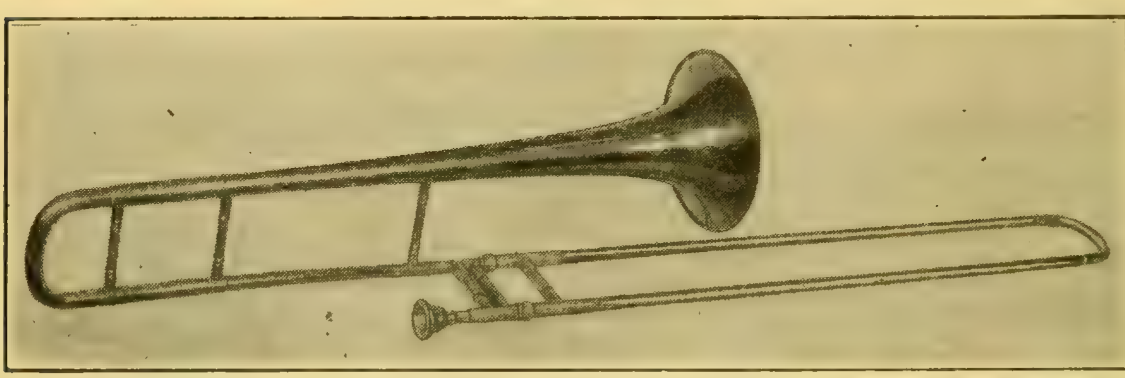


Figure 242. — The Diaphragm Is at the Center Node.

161. Wind Instruments. — In wind instruments different pitches are obtained by changing the length of the air column. This is done in the trombone (Figure 244) by the movements of the slide. In wind instruments like the flute, clarinet, and cornet, the length of the vibrating air column is varied by opening and closing holes. Opening a hole practically cuts off the air column at that point by forming an antinode.

By varying the method of vibrating the column and the shape of the column itself, different overtones are produced.

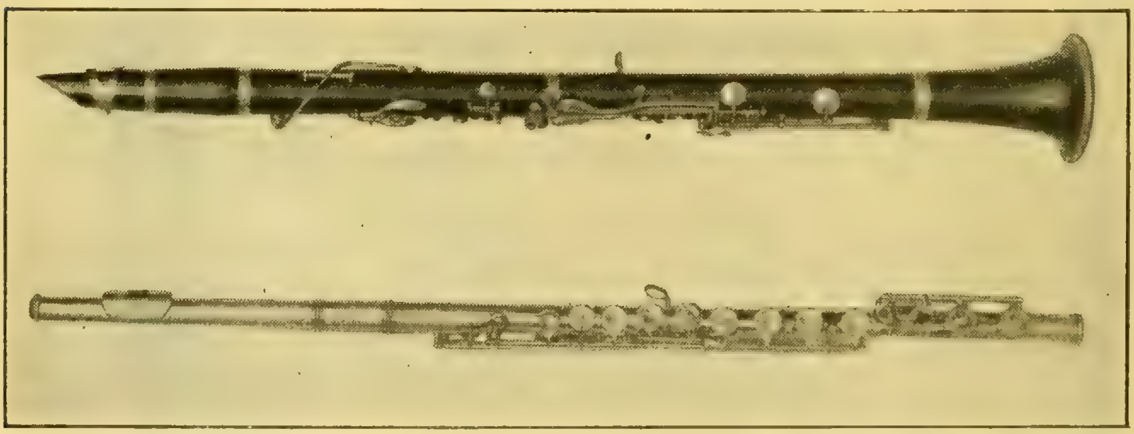


Courtesy Oliver Ditson Co.

FIGURE 244. — TROMBONE.

The U-shaped tube at the right slides outward on inner tubes attached to the mouthpiece and to the rest of the horn. Thus the length of the air column is changed.

Combinations of fundamentals with overtones give the different qualities of tones characteristic of different wind instruments.



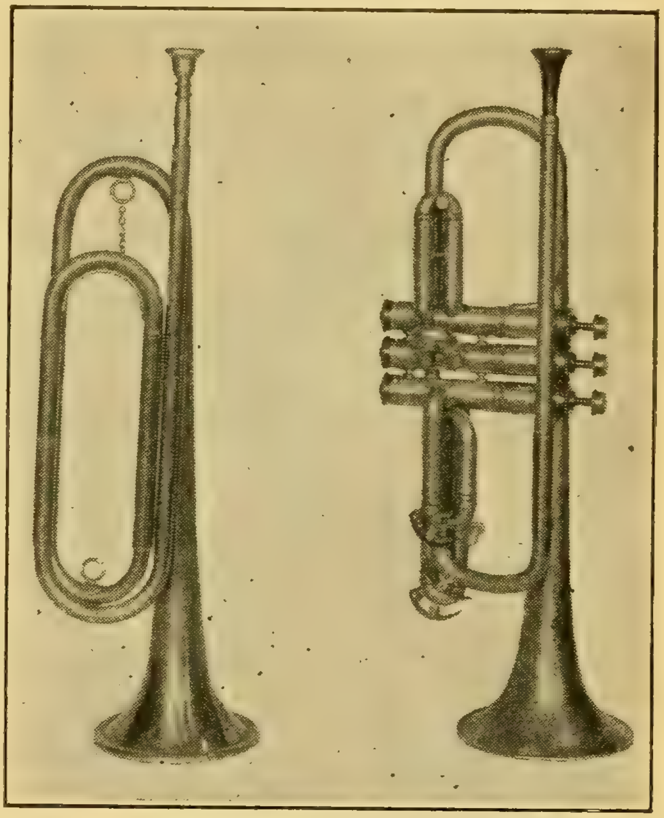
Courtesy Oliver Ditson Co.

FIGURE 245. — CLARINET (ABOVE) AND FLUTE.

The reed of the clarinet is flat and clamped parallel to a flat surface of the mouthpiece. As it vibrates, it admits and shuts off air. The mouthpiece of the flute is a hole seen near the left end across which air is blown.

The clarinet (Figure 245), which is vibrated by a reed, gives a great variety of overtones, while the flute, whose vibrations are produced by blowing against the sharp edge

of an opening, has relatively simple tone. The air column in the bugle (Figure 246) is set in vibration by the vibration of the lips; its notes are the fundamental and the simpler overtones. In the cornet, additional notes are produced by changing the length of the air column by means of valves.



Courtesy Oliver Ditson Co.

FIGURE 246. — BUGLE (LEFT) AND CORNET.

The bugle can sound only the fundamental and overtones. The change in length of air column in the cornet enables it to sound all the notes in its range.

QUESTIONS

1. What vibrates to produce sound in an organ pipe?

2. What is the difference in the construction of open and of closed pipes?

3. Compare the pitches of long and of short organ pipes.

4. What principle is illustrated by the use of the set of tubes mentioned in Experiment 71?

5. What is the relation between the length of two narrow open pipes differing in pitch by one octave?

6. State the law relating the length of a vibrating air column in a closed pipe to the frequency of the note produced.

7. Compare the pitch of an open pipe with that of a closed pipe of the same length.

8. What is the condition of the air at a node in an organ pipe?

9. Where is the node in an open pipe while sounding its fundamental note? In a closed pipe?

10. How long a wave is made by an open pipe 1 ft long? By a closed pipe of similar length?

11. At 20° C, how many waves from each of the above pipes will reach the ear in one second?

12. A middle C tuning fork produces a wave about 4.4 ft long. How long must an open pipe be to produce a similar wave?

13. How may notes of different pitch be produced by a flute? By a trombone?

14. State two ways by which the air in wind instruments may be set in vibration. Give examples of each.

15. How may a wind instrument produce different notes without change in length?

162. Resonance. — Vibrating air columns often reënforce the sounds produced by other vibrating bodies as in the case of wind instruments. The following experiment illustrates such reënforcement.

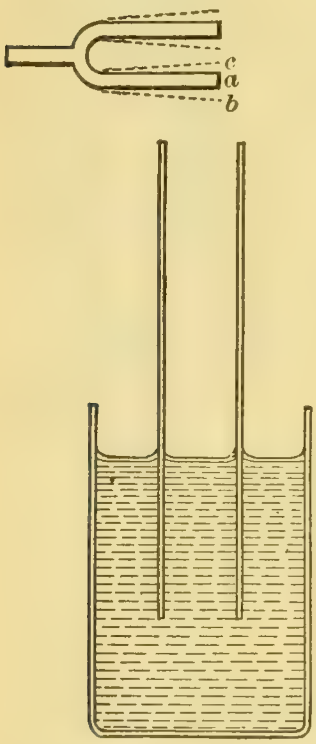


FIGURE 247.—The air column in the tube resonates with the fork.

EXPERIMENT 73. — Set a tuning fork in vibration and hold the prongs over the end of an open glass tube in the position shown in Figure 247. Raise or lower the tube in the jar of water until a position is located that gives the maximum loudness to the tone. Then the fork and the air column have the same vibration frequency, and the fork has set the air column into vibration. *How is the note of the fork made louder?*

When the length of the air column in Experiment 73 was adjusted so as to give the maximum loudness to the sound originated by the fork, the prongs of the fork vibrated in unison with the air column in the tube. When the prong at *a*, Figure 247, moves toward *b*, it starts a condensation down the tube. This impulse reaches the water at the bottom of the tube just as the prong arrives at *b*. The condensation is reflected by the water and gets back to *a* just as the prong does. The reflected impulse and the prong are then moving in the same direction and the reflected condensation intensifies the sound being produced by the fork,

As the prong moves toward *c*, it causes a rarefaction behind it. This also travels down the tube and back again while the prong is making half a vibration. These processes are continued so that there is a regular succession of reflected condensations and rarefactions that coincide with new sound

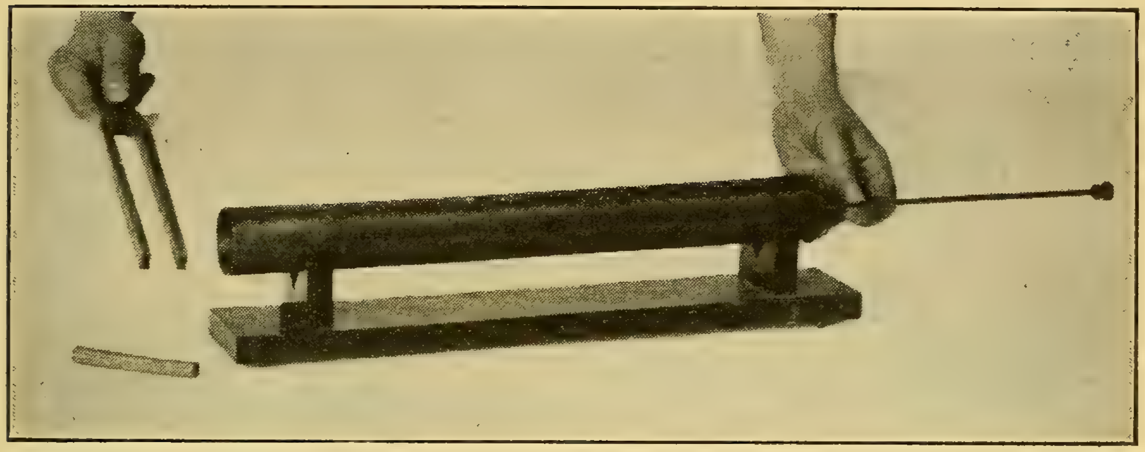


FIGURE 248. — CYLINDRICAL RESONANCE TUBE.

The length of the resonating column is adjusted by a piston.

waves being produced by the fork. The vibrations of the air column add their effect to the vibrations of the fork or give resonance to it.

When the length of the air column is adjusted so as to give the maximum resonance to the fork (Figure 248), a condensation has been found to go down the tube and back during a half vibration of the prong. During a whole vibration it travels twice as far, that is, four times the length of the resonating column (Figure 249). But, by § 149, a sound wave travels its own length during one vibration; therefore

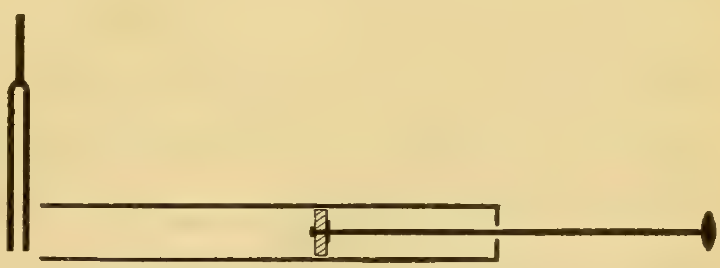


FIGURE 249. — SECTION OF RESONANCE TUBE.

The distance from the mouth of the tube to the piston is the length of the resonance column.

the length of the column is one quarter the length of the sound wave produced by the fork. When this relation holds, the fundamental of the vibrating air column has the same pitch as the tuning fork. In exact determination of the wave length of a resonant air column, two fifths of the diameter of the tube is added to the length before multiplying by four. In this case, resonance is the reënforcement of sound due to the union of direct and reflected sound waves.

163. Sympathetic Vibrations. — A clock spring delivers a succession of impulses to the pendulum so that it swings through a wide arc. Each impulse of the spring, however, is so small that it gives little motion to the pendulum. Yet if the tiny impulses are delivered at the same rate as the vibration frequency of the pendulum, the wide sweeping motion is produced. The effect of one vibrating body on another is also shown in an experiment with two tuning forks.

EXPERIMENT 74. — Use two C′ tuning forks mounted on resonance boxes and set them a short distance apart (Figure 250). Set one fork into vibration with a cello bow, and then touch the prongs so as to stop the vibrations. *From which fork does sound now come? What sets this fork into vibration?* Repeat the experiment, using forks of different frequencies. *Is the same result obtained? What frequencies must two forks have in order to produce sympathetic vibrations?*

One body can set another one into sympathetic vibration when the two have the same frequency. In such cases, the first wave from the vibrating body, when it strikes the other body, tends to start the latter into slight vibration. Since the period of the successive waves fits the natural period of vibration of the second body, a strong vibration is soon produced.

A marching column of men break step before crossing a bridge for fear the structure will be set into dangerous vibra-

tion. A diver adjusts his motions to the natural period of a springboard so as to get the maximum effect. A dangerous swaying of a moving car may be produced when people shift from side to side in unison with the car's period of vibration. Delicate glass vessels have been shattered by being set into

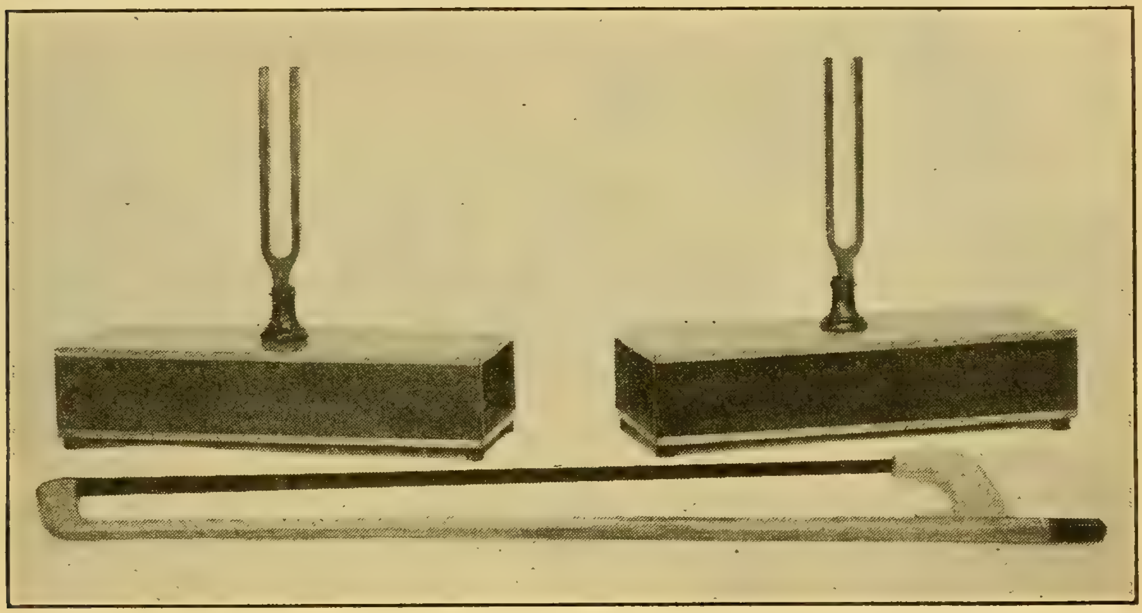


FIGURE 250. — The two tuning forks have the same frequency and each is mounted on a box in resonance with it. The bowed fork sends sound waves from the mouth of its resonance box; these produce sympathetic vibrations in the other box and fork.

sympathetic vibration by a note sounded on a musical instrument.

Resonance is the reënforcement of sound by sympathetic vibration. When the loud pedal of a piano is depressed and a tone sung into the instrument, the particular string in tune with the voice will respond. A sea shell held to the ear reënforces by sympathetic resonance such slight noises in the air as are in tune with the shell. Out of all the sound waves that pass the opening of the shell, only those are reënforced that vibrate in unison with the air in the shell. Upon this principle the Helmholtz spherical resonators (Figure 251) are based. They will respond only to tones which have

exactly the same vibration frequency and therefore can be used to determine the composition of complex tones. Vowel sounds are analyzed in this manner.

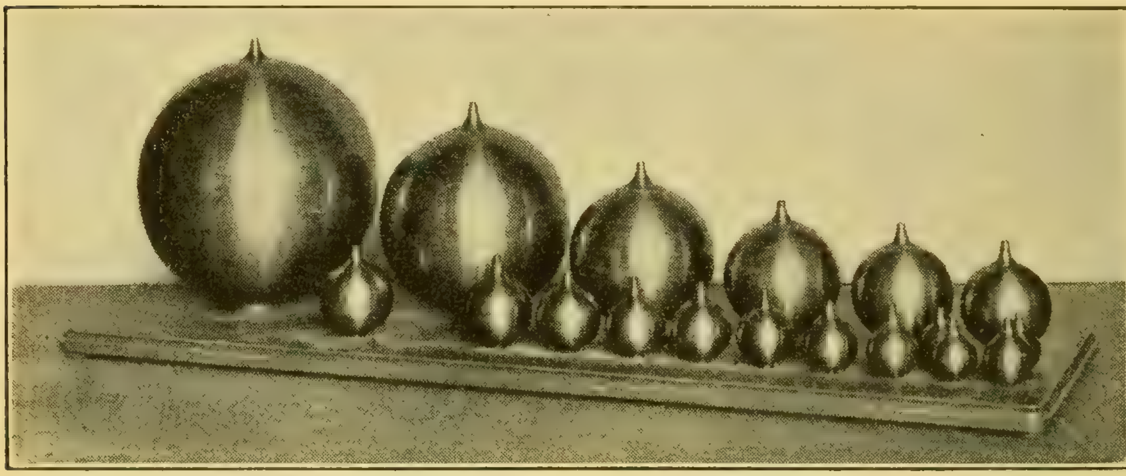


FIGURE 251. — HELMHOLTZ RESONATORS.

Each resonator responds loudly to a single pitch. If a string is tuned to one of them, its overtones can be readily detected by other resonators.

164. Interference. — We have seen that resonance occurs when the condensation of one sound wave combines with the condensation of the next wave. The following experiment shows what happens when a condensation and a rarefaction coincide.

EXPERIMENT 75. — Use the adjusted air column and fork of Experiment 73. Set the fork vibrating and rotate it over the top of the jar until a position of minimum loudness is found. Then slip a cardboard cylinder over one prong without touching it. *What effect is there on the loudness of the sound?* Without the cylinder a set of waves is sent out from each prong. When one prong is sending a condensation down the tube, the other is sending a rarefaction. The condensations of one set of waves tend to combine with the rarefactions of the other set. *How is the loudness affected if a condensation combines with a rarefaction?*

Hold the vibrating fork in an oblique position near the ear and slowly rotate the fork. Note the positions of the fork in which least loudness is obtained. *Explain how the rarefactions from one prong combine with the condensations from the other prong to produce this effect.*

Each prong of the fork in the last experiment sends out a train of waves of the same length. Where the condensations of one set combine with the condensations of the other, there is a maximum amplitude of vibration (Figure 252). If the ear is at this point, the loudest sound is heard. When a condensation combines with a rarefaction (Figure 253), minimum loudness is the result. One set of waves is then interfering with the sound being produced by the other. If these two sets of vibrations have the same amplitude, the combination of rarefactions with condensations results in silence. When the amplitudes are unequal, only a diminution in loudness occurs.

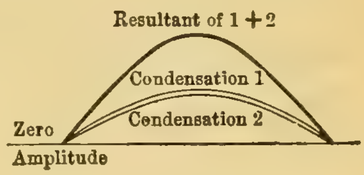


FIGURE 252.

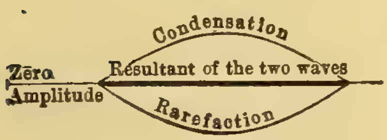


FIGURE 253.

165. Beats. — An interesting swelling and diminishing of sound occurs when the waves from vibrating bodies of slightly different frequencies combine. Two tuning forks of equal frequency can be used to illustrate this.

EXPERIMENT 76. — Put a rubber band on the prong of one of a pair of sympathetic tuning forks so that the added weight will make that fork vibrate a little slower than the other fork. Set the forks into vibration. Note how the sound increases in loudness and then dies away at regular intervals. This pulsating or throbbing of sound is known as the phenomenon of *beats*.

Beats occur when waves of slightly different frequency combine. At regular intervals condensation combines with condensation, giving a loud sound by reënforcement. At intermediate instants, condensations combine with rarefactions and their interference produces weak or even inaudible sounds. Hence the effect is a succession of loud sounds,

called *beats,* separated by intervals of relative silence (Figure 254).

Beats can be heard when you strike two adjoining keys in the bass of a piano. There is but little difference in frequency between the two notes, and the throbbing of sound continues for some time. Beats likewise can be obtained

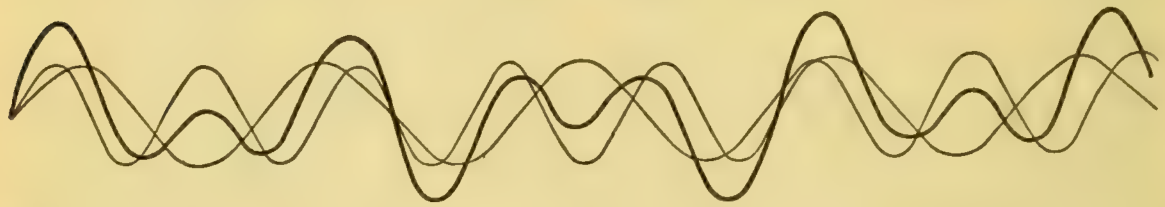


FIGURE 254. — BEATS.

The two light curves represent sets of sound waves having a vibration ratio of five to eight. The heavy curve represents the resultant sound. Four points of reënforcement and three of interference are shown.

with two organ pipes or with two whistles that vary little in pitch.

In these cases, the number of beats per second will equal the difference in frequency of the two sets of vibrations. Thus with two tuning forks generating respectively 256 and 252 vibrations per second, there will be four times in each second when the condensation from one fork combines with the condensation from the other. Thus four beats will be produced. The principles of sympathetic resonance and beats, applied to radio waves, are the principles upon which radio receivers are based.

QUESTIONS

1. Describe a simple experiment illustrating resonance.

2. What fraction of the wave length of a tuning fork is the length of an air column giving resonance to the fork?

3. How long must an air column be to give resonance to a tuning fork emitting waves 3 ft long?

4. Define resonance. Give illustrations of its importance in musical instruments.

5. Describe an experiment illustrating sympathetic vibrations. Under what conditions do they occur?

6. Give some common illustrations of sympathetic vibrations.

7. Give the principle and the use of spherical resonators.

8. How must a tuning fork be held over an air column of proper resonant length in order to produce interference?

9. Explain how one sound wave may combine with another to produce silence.

10. When and how are beats produced?

11. Two tuning forks of 250 and 256 v.p.s. respectively are sounded together. How many times per second do their condensations combine? What effect is produced when this occurs?

12. How many times per second do the condensations of one combine with the rarefactions of the other? What effect is produced by this combination of waves?

166. Musical Scale. — Music gives us pleasure because of its agreeable combinations of sounds. These pleasant combinations are not matters of chance but depend upon certain simple relations that exist between the vibration numbers of the musical notes. The simplest possible relation is 1 : 2, and this is the ratio that exists between the vibration numbers of the first and eighth notes of the musical scale, that is, 256 : 512. We call the first note, middle C (*do*), and the eighth note, upper C (*do*). The whole eight notes are called the *diatonic scale.*

A simple ratio, such as 3 : 2, 4 : 3, 5 : 4, 9 : 8, etc., exists between tones on the scale and the keynote. The eight tones are given names and numbers and are graphically represented by definite positions on the the musical staff, which consists of five parallel lines with the sign of the clef at the left (See Figure 255, p. 287).

Number names . .	1	2	3	4	5	6	7	8
Letter names . . .	c'	d'	e'	f'	g'	a'	b'	c''
Syllable names . . .	*do*	*re*	*mi*	*fa*	*sol*	*la*	*ti*	*do*
Vibration numbers .	256	288	320	341.3	384	426.6	480	512
Ratio of vibrations .	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2
Intervals		$\frac{9}{8}$	$\frac{10}{9}$	$\frac{16}{15}$	$\frac{9}{8}$	$\frac{10}{9}$	$\frac{9}{8}$	$\frac{16}{15}$

A scale for lower pitches (the bass) is made by taking c' as the eighth note. The first note or keynote must have a vibration number which is one half 256, or 128. The second note will have a vibration number $\frac{9}{8}$ times 128, or 144; the third note will have $\frac{5}{4}$ times 128, or 160, and so on. The number names, the syllable names, and the intervals will be the same as for the scale given in the table. The letter names will be c, d, e, f, g, a, b, and c'.

The scale can be extended similarly for higher pitches (treble) by taking c'' as the first note and using the same ratio numbers as before to determine the vibration numbers of the notes following. The eighth note, c''', or *octave* of the *first* will have double the frequency of c'', or 1024.

167. Chords and Intervals. — For many centuries it has been known that some combinations of tones are much more harmonious than others. A note and its octave are always recognized as a pleasing combination of sounds. The vibration numbers of two such tones stand in the simple ratio of 1 : 2. All musical tones in harmony have a simple ratio existing between their relative vibration numbers. When these have the simple ratio of 4 : 5 : 6, a particularly harmonious combination is obtained. The *major chords* of the diatonic scale are composed of three tones whose relative vibration numbers are in the 4 : 5 : 6 ratio. There are three such major chords: the *tonic*, c', e', g', or *do, mi, sol;* the *dominant*, g', b', d'', or *sol, ti, re;* and the *sub-dominant*, f', a', c'', or *fa, la, do.* An inspection of the line "ratio of

vibrations" in the table of the previous section shows that the tones of the three notes in each major chord have relative vibration numbers in the ratio of 4 : 5 : 6. Similar major chords exist in the scales that are above or below the one just mentioned.

Minor chords are composed of three tones whose relative vibration numbers stand in the simple ratio of 10 : 12 : 15.

There are three important intervals between *do* and the other notes of the diatonic scale. The *major third* is the interval between *do* and *mi* (ratio 4 : 5); the *fifth*, the interval between *do* and *sol* (ratio 2 : 3); and the *octave*, the interval between *do* and *do* (ratio 1 : 2).

168. Chromatic Scale. — The key of D has d' for its key-note with a vibration number of 288. If this number is multiplied by the "ratio of vibrations," $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{5}{3}$, $\frac{15}{8}$, and 2, vibration numbers for the seven other tones in the scale of this key are found. Tabulating the results:

	c'	d'	e'	f'	g'	a'	b'	c''	d''
Key of C . .	256	288	320	341.3	384	426.6	480	512	576
Key of D . .		288	324	360	384	432	480	540	576

It will be noted that there is a close agreement of the vibration numbers of the corresponding notes in the two keys, except those for f' and c''. To remedy this and in order to have the intervals in the key of D about the same as those in the key of C, musicians introduce two new semitones, $f'\sharp$ and $c''\sharp$, when playing the key of D.

The vibration number of a *sharp* is $\frac{25}{24}$ of the vibration number of the note from which it is derived. In constructing the scale for other keys, some notes have to be flatted. The vibration number of a *flat* is $\frac{24}{25}$ of the frequency of the note from which it is derived. Five of these semitones are

needed in the construction of the scales for the different keys.

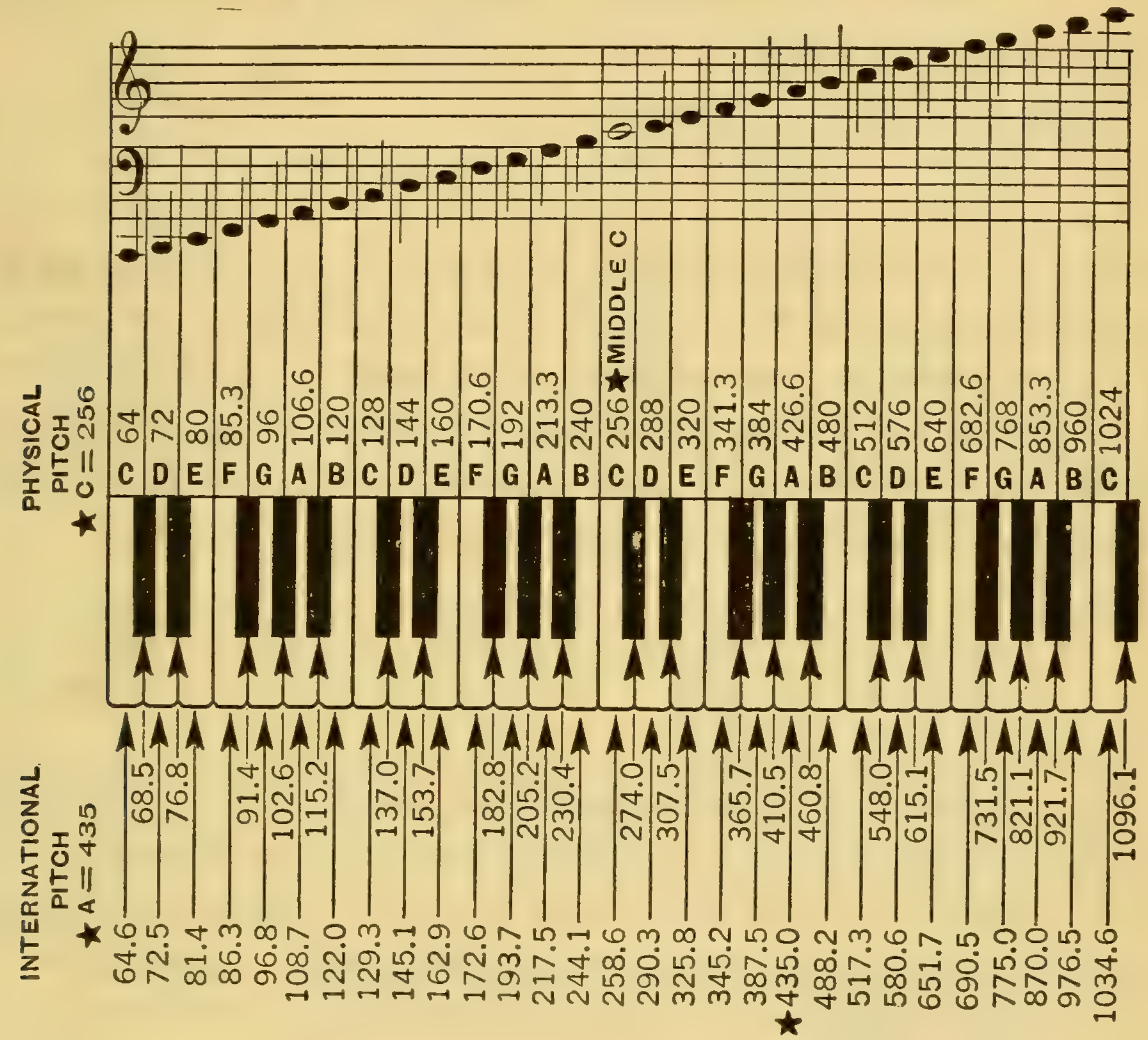
The *chromatic scale* in any octave consists of the eight regular tones of the diatonic scale and five semitones. The white keys on a piano are for the eight regular tones in the key of C, while the black keys serve for the semitones (sharps and flats).

169. Even-Tempered Scale. — In constructing the chromatic scale, slight variations between the frequencies of corresponding notes, such as e' and a' in the keys of C and D, are not remedied. To correct all the differences arising in the building of the several keys would give about 70 notes to an octave. This is an impossible number for usable keyboards.

To get regular intervals between the tones of the scale whatever may be the key, the *even-tempered scale* has been devised. It consists of 13 tones with equal intervals between. Each note, then, is a semitone. Since there are 12 intervals and since the vibration number of the octave is twice that of its keynote, $\sqrt[12]{\frac{2}{1}}$ or $\sqrt[12]{2}$ will be the ratio number of the semitone interval. $\sqrt[12]{2}$ is approximately 1.06. The vibration number of each tone is found by multiplying the frequency of the preceding tone by 1.06. The even-tempered scale is the scale used with most musical instruments (Figure 255).

170. Standard Pitch. — It is unfortunate that there are several standards for pitch. The standard tuning fork of physical laboratories is the middle C (c') with 256 vibrations per second. This makes a' have a frequency of 427. The standard for International Pitch, however, is a' with a frequency of 435. The American Federation of Musicians

have adopted still another standard, 440 for a'. There is still another for Concert Pitch, which is rapidly going out of use.



Courtesy of Standard Scientific Co.

FIGURE 255. — In this chart of an even-tempered scale the position of the notes on the staff is shown at the top and the corresponding piano keys below, with their frequencies in physical pitch and International Pitch.

SUMMARY

The three **laws of vibrating strings** are: (1) **Length**: The vibration frequency is inversely proportional to the length (tension and mass constant). (2) **Tension**: The vibration frequency is directly proportional to the square root of the tension (length and mass constant). (3) **Mass**: The vibration frequency is inversely proportional to the square root of the mass per unit length of the string (tension and length constant).

Stringed instruments produce their wide range of notes by the application of the three laws of strings. Long, loose, large strings give low notes; short, stretched, small strings give high notes. Tuning is accomplished by adjusting the tension.

Organ pipes give sound because the air in them vibrates longitudinally when air is blown into the bottom of the pipes.

The **vibration frequency** of an organ pipe is determined by the length of the vibrating air column in it. A short pipe gives a note of a higher pitch than a longer one, or, the vibration frequency of a pipe is **inversely proportional to its length.** A **closed pipe** gives a tone an octave lower than an open pipe of the same length. The length of a closed pipe is about one fourth the length of the wave made by the pipe. There is a node at the closed end.

The length of an **open pipe** is about one half the length of the wave made by the pipe. There is a node at the center of the pipe.

The **pitches of wind instruments** are obtained by varying the length of the air column. By varying the method of vibrating the column and the shape of the column itself, different overtones are produced. Combinations of fundamentals with overtones give the different qualities of tones characteristic of different wind instruments.

Vibrating air columns often reënforce the sounds produced by other vibrating bodies. When the length of the vibrating air column is one quarter the length of the sound wave produced by a tuning fork, the fundamental of the vibrating air column has the same pitch as the tuning fork.

The union of the direct and the reflected sound waves produces **resonance.**

Sympathetic vibrations depend upon an exact equality in the vibration frequency of two bodies. When one body is set into vibration, the other tends to vibrate also, since the period of the successive waves sent out by the first body fits the natural period

of vibration of the second body. When this is set into motion, the waves from the two bodies help each other and a strong vibration is soon produced.

Resonance is defined as the reënforcement of sound by sympathetic vibration. Spherical or Helmholtz **resonators** respond only to the tones of the same vibration frequency. They are used to analyze sounds.

Interference of two sets of sound waves occurs when the wave lengths of the two sets are about equal, and when the condensations of one set combine with the rarefactions of the other set. If the two sets of vibrations have the same amplitude, the combination of rarefactions with condensations results in silence. When the amplitudes are unequal, only a diminution in loudness occurs.

Beats occur when sound waves of slightly different frequency combine. At regular intervals, condensation combines with condensation, giving a loud sound by reënforcement. At intermediate instants, condensations combine with rarefactions and the interference thus caused produces weak or even inaudible sound. The effect is a succession of loud sounds, called beats, separated by periods of silence.

The diatonic musical scale consists of eight tones with the eighth tone having double the number of vibrations of the first tone or keynote. A simple ratio exists between the vibration numbers of successive notes on the scale.

The major chords of the diatonic scale are composed of three tones whose relative vibration numbers are in the ratio of 4 : 5 : 6. For the minor chords, the relative vibrations of the three tones are 10 : 12 : 15. **The important intervals** are the major third, the fifth, and the octave.

The chromatic scale in any octave consists of the eight regular tones of the diatonic scale and five semitones, known as sharps and flats. **The even-tempered** scale consists of thirteen tones with equal intervals between. It is the scale generally used with musical instruments.

The **standard pitch** of the physicist is $c' = 256$ ($a' = 427$); of International Pitch, $a' = 435$; and of the American Federation of Musicians, $a' = 440$.

EXERCISES

1. Describe an experiment with a sonometer that illustrates the law of vibrating strings.

2. If 21.3 inches of a vibrating string have a frequency of 256, what length will give a frequency of 426, provided the tension remains the same?

3. What change takes place in the vocal chords as a person sings the ascending scale? Explain.

4. What law of strings is illustrated by the triangular shape of a harp or of a grand piano? Show how the two other laws of strings are applied in the piano.

5. Where should the string of a musical instrument be stopped in order to make it sound an octave higher? Explain.

6. What methods does a violinist use to produce notes of different pitch?

7. Compare the pitch of an organ pipe 12 feet long with the pitch of one 4 feet in length.

8. What is the condition of the air at the ends and at the center of a sounding, open organ pipe? In a closed pipe? Why?

9. Account for the production of tones of different pitch in a trombone; in a cornet; in a flute.

10. A resonant air column 12 inches long and 2 inches in diameter resounds to a tuning fork. (*a*) What is the length of the wave emitted by the fork? (*b*) How many vibrations does the fork make in a second? (*c*) How many vibrations does the air column make in a second?

11. Compare the frequency at 0° C of an open pipe 2 feet long with its frequency at 20° C. Does an organ pipe have a fixed pitch? Explain.

12. How long should an open pipe be to produce g' (384 vibrations) at 15° C?

13. How is resonance given to the vibrating strings of (*a*) a piano; (*b*) a mandolin; (*c*) a violin?

14. The longest tubes used in organ construction are closed ones 9 feet long. What is their frequency at 20° C?

15. How are vibrations of the vocal cords reënforced, so that the voice has resonance?

16. In order to increase the strength of its tone, a doorbell making 1000 vibrations a second has placed near it a resonant air column. What should be the length of the air column?

17. A resonant column, supplied with a constant flow of carbon dioxide gas, had to be adjusted to a length of 9 inches in order to respond to a fork making 256 vibrations per second. What must be the velocity of sound in carbon dioxide?

18. Why do window panes sometimes rattle when a pipe organ is being played?

19. How many beats per second will be given by two A tuning forks whose respective frequencies are 427 and 435?

20. It is desired to determine the frequency of a new tuning fork. It appears to be slightly sharper than a standard fork making 256 vibrations per second. When the forks are sounded together, 3 beats are heard each second. What is the frequency of the new fork?

21. How does a piano tuner make use of beats in tuning a piano?

22. Calculate the vibration numbers of the eight tones of the octave in the diatonic scale whose keynote is c''.

CHAPTER XIV

HOW LIGHT BEHAVES

Introduction

171. Historical. — The science of light is perhaps the oldest of the branches of modern physics. Centuries before the Christian era, men had made vague attempts to explain the simple facts of vision, although no real progress was made in explaining the true nature of light. Reflection by plane, spherical, and parabolic mirrors was studied by the Greeks and the phenomena of refraction were known. Aristotle made an effort to explain the rainbow and refraction, but unfortunately left certain false impressions which were still current at the time of Kepler (1600 A.D.). During the Dark Ages of European history, science was kept alive by the Moors. In the tenth century, we find Alhazen, a Moorish scientist, making observations concerning refraction, studying the laws of reflection, and giving an account of the function of the eye in vision. He is the first man on record to note the effect of lenses.

By the beginning of the seventeenth century, the use of lenses for spectacles had become commonplace and the discovery of the telescope is said to have resulted from the play of two children of a Dutch lens maker. Galileo, learning of this invention, set about making a telescope for himself. He made one of different design and with it observed the moons of Jupiter and laid the foundations of his defense of the

modern belief in the revolution of the earth about the sun (1610).

Galileo's contemporary, Kepler, gave us the first adequate statement of the meaning of vision. Kepler declared that seeing is a sensation taken to the brain by the mechanism of the eye and the optic nerve. Kepler is also responsible for the statement of the law of inverse squares to be discussed in a later paragraph. He likewise measured the angles of incidence and of refraction of various media, but left the statement of the law of refraction to Snellius (1621).

Newton, living from 1642 well into the next century, did some remarkable work on light while still a young man. He performed the dispersion experiment described in § 193 and gave the proper interpretation of the different colors in the spectrum as well as of the rainbow. Newton relied upon, but did not insist upon the emission theory of light, that is, that light is a stream of particles given off by visible objects. As previously noted, Newton's contemporary, Huygens, formulated the wave theory of light, which was disregarded until revived by Young in 1815 and further elaborated by Fresnel at about the same time. Halley, Newton's pupil and publisher, derived the formula for lenses discussed in § 425.

The development of the telescope and the microscope progressed slowly, because of the inability of lens makers to avoid chromatic and spheric aberration (§§ 427, 428). It was not until 1758 that the telescope was freed from the color fringes. The compound microscope fell into disuse until about 1800, when compound lenses were made to overcome these defects.

Fraunhofer contributed his work on spectra and spectrum analysis in 1815, while Bunsen and Kirchhoff perfected the spectroscope in 1859. The latter published a paper on the analysis of the stars by means of the spectroscope in 1879.

The exact nature of the disturbance which causes light and the mechanism by which it is transmitted is at present a matter of much discussion. The wave theory explains satisfactorily the common phenomena of light, but some of the more obscure things do not seem to be covered by it. This points to a modification of the theory in such manner as to retain the valuable features of the old theory and to include the newer ideas involved in Plank's quantum theory. The matter is still in the realm of higher mathematics.

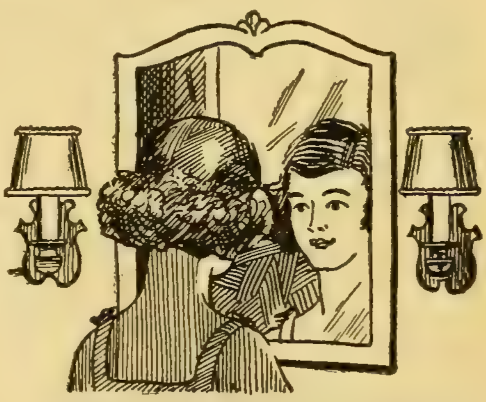
It is of interest to note the relationship between physics and the two allied sciences, mathematics and astronomy. Archimedes was primarily a mathematician and thought but little of his physical discoveries. Galileo acquired much of his fame as an astronomer, although his work on mechanics is of more importance. Kepler was an astronomer and a mathematician who nevertheless made valuable contributions to physics. Römer was an astronomer, but discovered that light has a measurable velocity. Newton was mathematician enough to invent the calculus; astronomer enough to devise an explanation for the movements of the earth and the other planets; and physicist enough to add much to the previous knowledge about color, sound, mechanics, and other topics. There has always been a tendency to reduce physical phenomena to a mathematical basis, doubtless because most quantities must be measurable in order to be useful.

172. Light and Man. — Man, like the other animate things, is the result of his surroundings. His development depends upon his environment — air, water, heat, food, and light. His progress has exceeded that of the other animals because of his ability to understand and modify these conditions. In one manner or another, he is dependent upon light, not only for his comfort and convenience, but for his

life. From the standpoint of the biologist, light is important because it brings about the production of food plants that man uses directly, or feeds to his meat-producing animals. Light also kills bacteria that cause disease. From a physical standpoint, light is the stimulus to the optic nerve and is therefore the cause of vision.

The Path of Light

173. Visibility. — Vision occurs when enough light from any object enters the eye and forms an image on the retina. The light may originate from the object itself, in which case the object is said to be *luminous.* Or the light may be simply reflected to the eye by a body, which is called an *illuminated* body. The sun and the stars are luminous bodies, being visible by their own light. The moon and the planets are illuminated bodies, being visible by light which they reflect. Most common objects are illuminated bodies (Figure 256).



Courtesy National Lamp Works of Gen. Elec. Co.

FIGURE 256.—Light from the electric lamps goes first to the face, then to the mirror, and then to the eyes.

Substances through which light will not pass are *opaque;* if *some* light passes through the body, but not enough to permit objects to be clearly seen, the body is *translucent;* if objects can be clearly seen through a body, the body is *transparent.* Glass is transparent in thin sheets; window shades and curtains are usually translucent; wood and stone are opaque. Transparency depends upon thickness; many substances, such as paper, gold, and cloth, usually considered to be opaque, are transparent when sufficiently thin.

174. Light Travels in Straight Lines. — From childhood, we have been accustomed to reaching directly for objects that we wish to touch. Even then we were acting on the principle that light travels in straight lines. Light travels by means of waves. As long as it travels through one kind of substance, the light proceeds in all directions in straight lines from its source. This fact is well illustrated by a simple

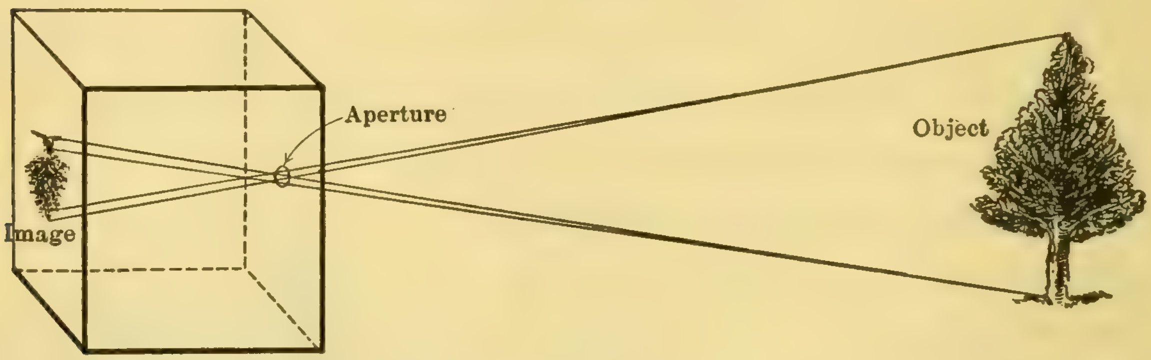


FIGURE 257. — A pinhole camera lets light from an object pass through a small opening and form an *inverted image* upon the opposite side.

device known as the *pinhole camera* (Figure 257). Light from a candle or other source is allowed to pass through a small opening in the side of a box. The opposite side of the box is a ground glass plate, on which an inverted image of the source of light will be seen. The image is composed of separate spots of light overlapping. Each spot consists of light that has come through the aperture from one point in the object. Light from the top of the object passes straight through the aperture and forms the bottom of the image. The top of the image is formed by light from the bottom of the object.

175. Images in the Eye. — A very small opening permits the formation of a dim but sharp image. A larger opening causes the image to be brighter but less distinct in outline. The eye and the photographic camera form inverted images

by light that passes through small openings (Figure 258). The aperture of the eye, known as the pupil, involuntarily dilates when the light is dim and contracts when the light is bright, but it is always large enough to form hazy, indistinct images. This indistinctness is prevented in both the eye and the camera by the use of a lens that causes all the light that leaves one point of the object to fall on one point of the sensitive screen, instead of forming a spot that over-

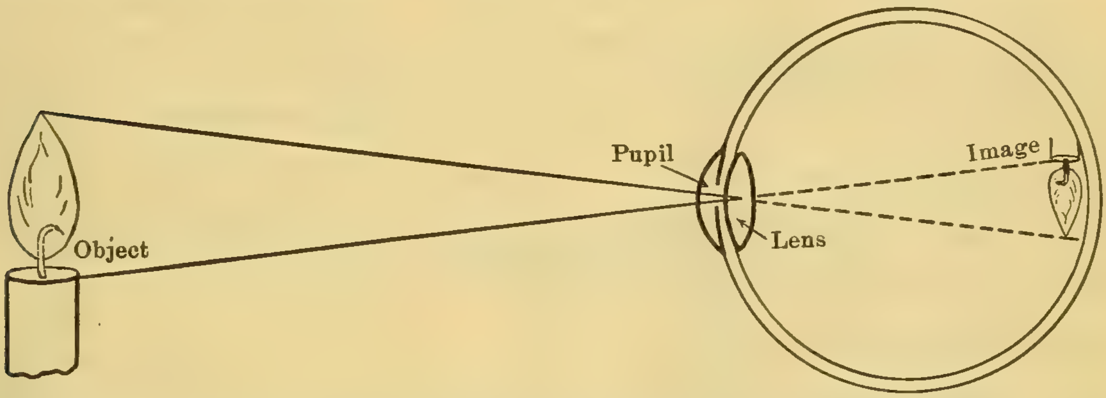


FIGURE 258. — The eye forms images just as the pinhole camera does except that a lens makes a sharp image.

laps the spots of light from other points in the object. Inverted camera images are simply turned bottom side up to make the image appear in proper position. Images formed on the retina of the eye are unconsciously interpreted by the brain as being erect. The brain also forms an estimate of the proper size of objects by previous experience, without much regard to the size of the image formed by the eye.

176. Shadows. — Since light travels in straight lines as long as it remains in the same medium of transmission, it follows that opaque objects will exclude light from the space on the side away from the source of light. The area thus darkened is a *shadow*. If the light is emitted from a single point, the resulting shadow will have a sharp outline, and will be of uniform intensity. Such a shadow is called an

umbra. An electric arc emits lights from a small area and hence casts an umbra (Figure 259). If the light comes from a source of greater area, an opaque body cuts off light entirely from *some* of the space behind it, while only a portion of the light is cut off from the remaining space. The totally darkened space is called an umbra, as above, and the partially darkened space is called a *penumbra* (Figure 260). If the luminous body is larger than the opaque body, the umbra diminishes to a point and disappears (Figure 261).

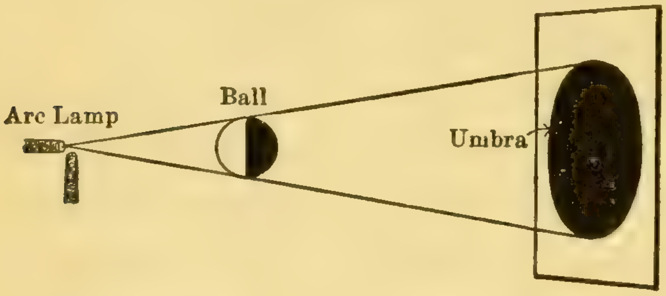


FIGURE 259. — Light from a "point source" casts a sharp shadow of uniform intensity, called an *umbra.*

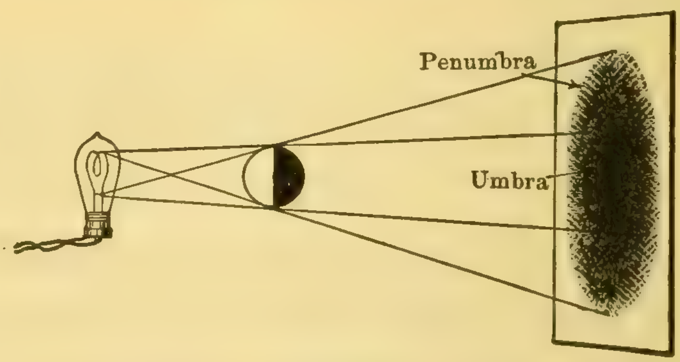


FIGURE 260. — Light from a broad source forms shadows with an umbral center, bordered with a *penumbra* or partial shadow.

177. Eclipses. — An interesting illustration of shadow formation is found in an eclipse, or the darkening of the sun or moon. The moon is not a luminous body, so when it enters the earth's shadow, it is darkened. As the moon revolves around the earth, it usually passes above or below the earth's shadow, but occasionally the earth stands exactly between the sun and the moon. Then persons living on

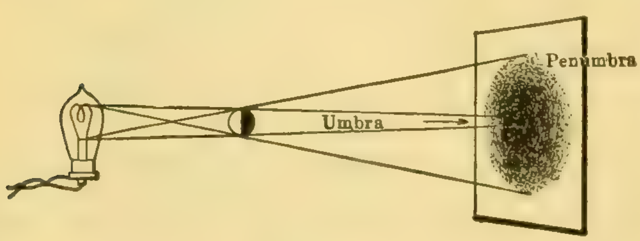


FIGURE 261. — If the opaque body is smaller than the luminous body, the umbra tapers to a point and disappears.

the side of the earth toward the moon see an eclipse of the moon (Figure 262).

Solar eclipses are less common than lunar eclipses for ordinary observers, because they are visible over a much smaller area. When the moon's shadow extends toward the earth, without the umbral portion reaching the earth (Figure 263, bottom), a ring or *annular* eclipse occurs. At times the moon is near enough to the earth so that its umbra, a few miles in diameter, falls upon the earth (Figure 263, top). The rotation of the earth causes this darkened spot to traverse a strip in which the sun appears totally obscured. On each side of this strip, where the eclipse is total, is an area covered by the penumbra of the moon. People living in these areas see the sun partly darkened, as though a piece had been taken out of it. To such observers, the eclipse appears as a *partial solar eclipse*.

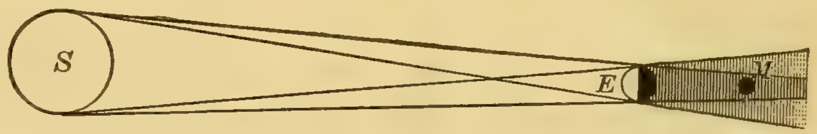


FIGURE 262. — A *lunar eclipse* is caused by the moon entering the earth's shadow.

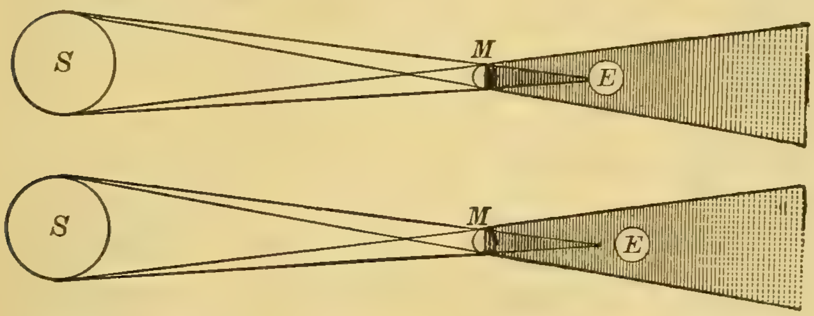


FIGURE 263. — A *solar eclipse* occurs when the moon's umbral shadow touches the earth (above). An observer directly behind the tip of the moon's shadow would see the sun as a bright ring with a dark center (below). Correct proportions are impossible because of great distances involved.

QUESTIONS

1. What are luminous bodies? How are non-luminous bodies seen?
2. What difference exists between opaque, translucent, and transparent bodies? Give an example of each.

3. How is an image formed by a pinhole camera?

4. Describe the image formed by a pinhole camera.

5. What is a shadow? How is a shadow formed?

6. Illustrate by a diagram the formation of a shadow by an opaque body placed in the light coming from a point. What is the nature of the shadow?

7. Illustrate the formation of a shadow produced when an opaque body is placed in the light from a broad source. Name the different parts of the shadow.

8. What are eclipses? What surface is darkened during a solar eclipse?

9. Why is the moon visible? Where is the moon during a solar eclipse?

10. Compare the eye and the camera with the pinhole camera, in regard to the formation of images.

Reflection

178. Reflection. — When sunlight falls upon a piece of glass, it will pass through the glass. If the glass is colored, part of the light is absorbed. If the glass is silvered, the light will be turned back by the silvered surface into the same medium in which it had been traveling. This return of the light into the same medium in which it had been traveling is *reflection.* The reflection of light may be likened to the rebounding of a rubber ball from a wall against which it is thrown. The ball either returns along its former path or takes a new path back through the air. Moreover, if the wall is smooth, the path of the ball after rebounding can be closely estimated. From a rough surface the ball is reflected in an uncertain manner.

Now when a ray[1] of light strikes upon a reflecting surface

[1] The word *ray* is used to denote a narrow portion of a light stream. The term has no physical significance and is used only as a convenience to express the idea of a *line of light.*

the same things are true of it as are true of the ball. The difference in its reflection by smooth and by rough surfaces produces widely different results. The following experiment shows reflection from a smooth surface:

EXPERIMENT 77. — Mount a plane mirror at the center of a circle divided into degrees (Figure 264). Let a ray of light, coming through a slit, fall upon the mirror at right angles. *What is the path of the reflected ray?* Change the position of the mirror so that the ray strikes at some other angle with the mirror. Draw a perpendicular (*normal*) to the mirror at the point where the ray strikes the reflecting surface. Measure the angle between the ray falling on the surface and the normal. Measure the angle between the ray leaving the surface and the normal. *How do these two angles compare in size?*

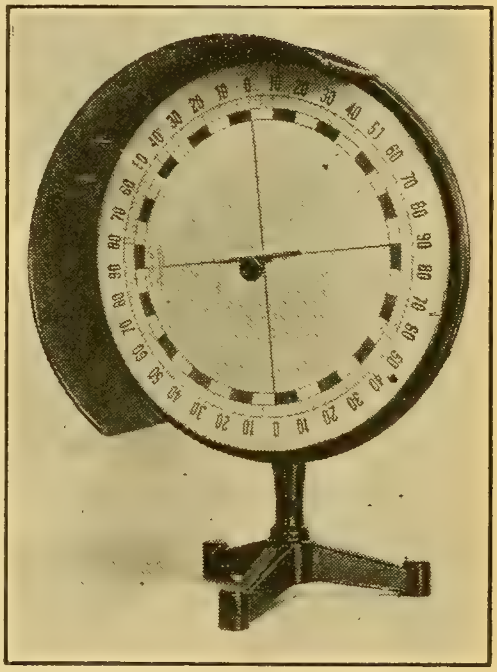


FIGURE 264. — THE LAW OF REFLECTION ILLUSTRATED.

The ray striking the mirror is called the *incident* ray and the angle between this ray and the normal is the *angle of incidence.* The ray leaving the mirror is the *reflected* ray and its angle with the normal is the *angle of reflection.* We find that, no matter how the light strikes the reflecting surface, it rebounds from that surface so that *the angle of reflection equals the angle of incidence and lies in the same plane.* This is the *law of reflection.*

179. Regular Reflection. — When light comes to the eye directly from a lamp, the different parts of the oncoming stream of light maintain their same relative positions with regard to each other. This regularity causes a clear image of the lamp to be formed by the eye. Let us now see by experi-

ment how a mirror affects the position of different parts of a stream of light falling on it. An ordinary mirror is a plane, often made by silvering one side of a piece of glass. This process combines the smoothness of glass with the reflecting property of silver. On such a surface let fall light from a number of parallel slits illuminated by sunlight or a distant arc light (Figure 265). We observe that while the incident beams, 1, 2, 3, 4, 5 (Figure 266), are apparently reversed in order, their relative position is the same as before reflection. By another experiment, let us see how such a reflected beam affects our eye.

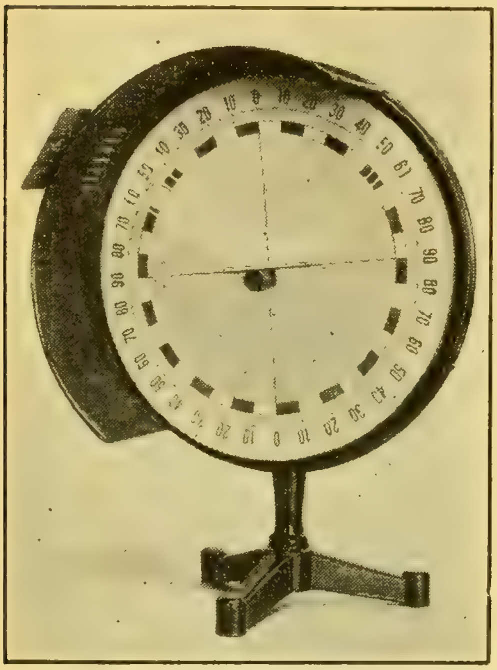


FIGURE 265. — Rays parallel to each other before falling on the plane mirror are parallel after being reflected.

EXPERIMENT 78. — In a darkened room, stand a candle or other luminous body before a vertical pane of glass (Figure 267). The glass reflects enough light to form a clear image of the candle. This image is seen to be erect, and to all appearances of the same size as the object candle. Look through the glass and set a similar candle so that it occupies the space where the image of the first candle appears to be.

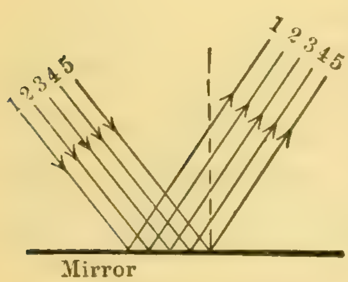


FIGURE 266. — Light is *regularly* reflected if the rays leave the reflecting surface in the same relative order as they fall on it.

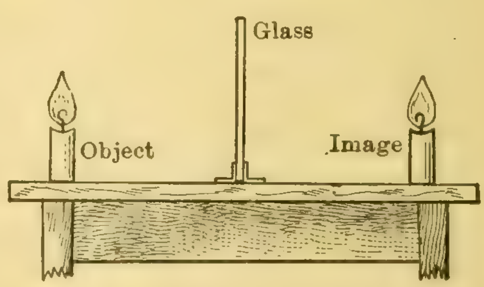


FIGURE 267. — The glass reflects a part of the light from the candle; an erect, virtual image as large as the candle is formed as far behind the glass as the candle is in front of it.

The distance of the second candle shows that the image is as far perpendicularly behind the mirror as the object is in front of the mirror. The stream of light from the candle has fallen upon the mirror with its parts in a certain relative order. The mirror has reflected these parts in the same relative order, and so the eye forms the same kind of image of the reflected light as it would form if the light entered the eye directly. Since the beams are reflected in their reverse order, the image of print seen in a mirror is reversed from right to left. All plane-mirror images undergo a similar *lateral reversion.* The reflection of light in such a manner that the parts of the wave keep their same relative positions is called *regular reflection.* A surface that reflects light regularly is itself invisible, but it produces clear images of any objects that send light to it.

A quiet pool of water forms images symmetrical with the landscapes that send light to the pools (Figure 268). Window-glass, although permitting much light to pass through it, reflects light enough to make images. If the space behind the glass is dark, as that outside our windows at night, the glass forms an image of our brightly lighted room. This image is so distinct that it obscures the dim objects outside. Somewhat the same effect is produced by store windows, if the interior is dim. Show windows in stores are brightly lighted so that persons standing outside will see the display inside, rather than an image of themselves.

It must be kept in mind that in every case thus far, the *real* light is reflected in front of the mirror, but the image is always behind the mirror. Since no light goes through the mirror to make this image, the image is not real but *virtual,* that is, not having a real existence, but being apparent to the eye.

180. Diffuse Reflection. — Reflection of light is much more common than is usually believed. Very few surfaces fail to return some of the light which falls on them. Our ideas of reflection are generally concerned with the regular reflection of light by mirrors. There is a different kind of reflection, of much greater importance, from the surfaces of

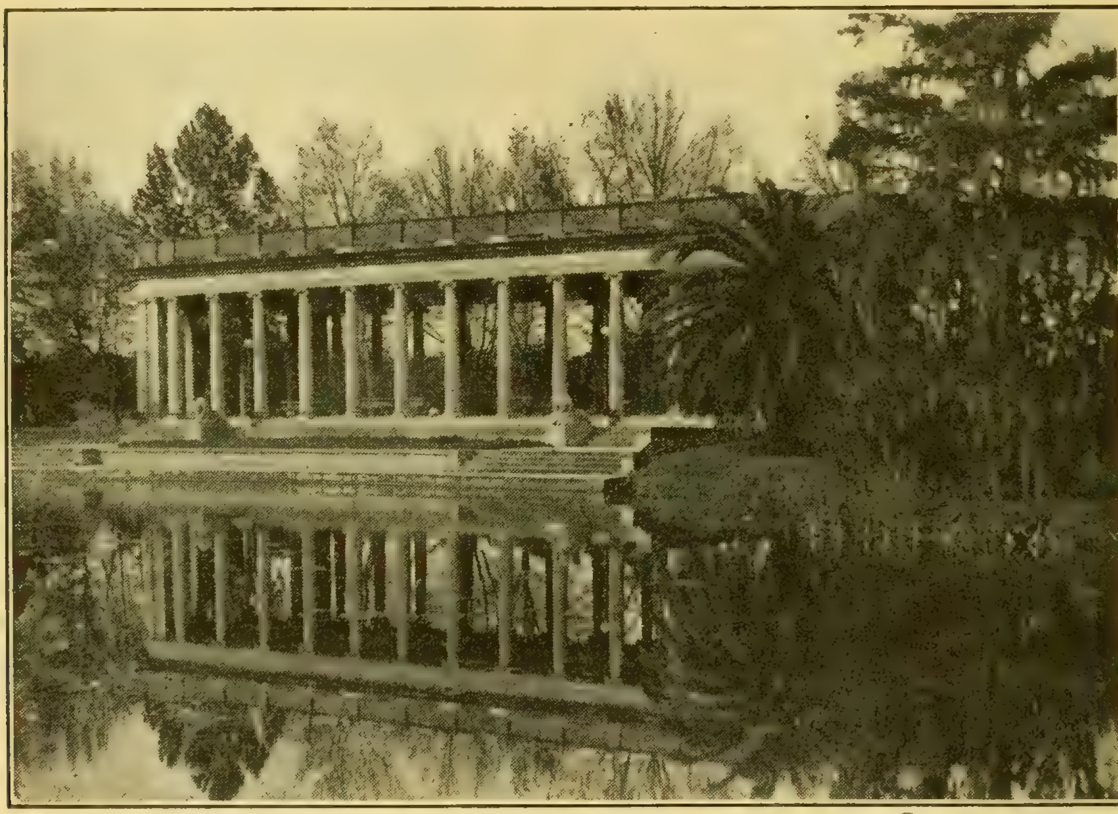


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FIGURE 268. — A horizontal mirror, such as a quiet pool, forms inverted images just as a vertical mirror forms images reversed from left to right.

the common objects around us. This is called *diffuse reflection*. We have seen that smooth surfaces reflect light so that the light stream is unchanged. If light falls on a rough surface, however, each tiny elevation is lighted up and sends out light in all directions just as a luminous body does. The rays are no longer reflected in the same relative order as that in which they strike (Figure 269). Suppose that a sheet of paper receives light from a lamp. The paper that is smooth to the touch really has a surface that is seen to be irregular if

viewed through a strong magnifying glass. The sheet of paper will reflect nearly all the light that falls on it, but the *reflecting surface* and not the *source of light* is seen.

181. Importance of Diffuse Reflection. — Diffuse reflection tends to produce a uniform distribution of light because the light is reflected from the rough surfaces in *all* directions. This means that areas that would otherwise be dark, lacking direct illumination, are lighted by the rays that are sent to them by diffuse reflection from adjacent rough surfaces. Clouds, dust, and smoke particles in the air, whitewashed basement walls, and light-colored paints and papers in our houses all help to illuminate corners that receive no direct light. Without diffuse reflection, the sky would be dark in daytime, and a person walking into the shade of a building would be in total darkness.

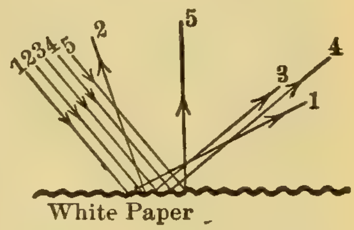


FIGURE 269. — *Diffuse Reflection* takes place when light is scattered irregularly by uneven surfaces. For each ray, the angle of reflection equals the angle of incidence.

Another effect of diffuse reflection is the visibility of non-luminous objects. We see people, furniture, vehicles, and all common articles, except lamps, by this means. Each article is a reflector that is itself visible rather than the lamp or the sun that illuminates it.

There is no fixed division between *rough* and *smooth* surfaces, hence a surface may regularly reflect some light while some is diffusely reflected. Walls of a room should be covered with a paint that leaves a surface rough enough to reflect the light diffusely. This prevents the glare that would result from regular reflection from a glossy surface. For the same reason, books should be printed on rough paper to prevent regular reflection that shows the light but not the surface.

Surfaces vary greatly in their ability to reflect light diffusely. No surface reflects all the light that falls on it. If the surface reflects nearly all the light that it receives, it is called *white*. If light falls on a smoked surface, practically all of it is absorbed and the surface is *black*. Intermediate surfaces that are not selective in their absorption are gray. Surfaces that select certain portions of the light to absorb and reflect the remaining portions are known by the name of the light they reflect, as red, green, blue, etc. Light-colored walls reflect a much larger percentage of the light falling on them than dark walls do, and for this reason should be selected for interiors that have an inadequate supply of light.

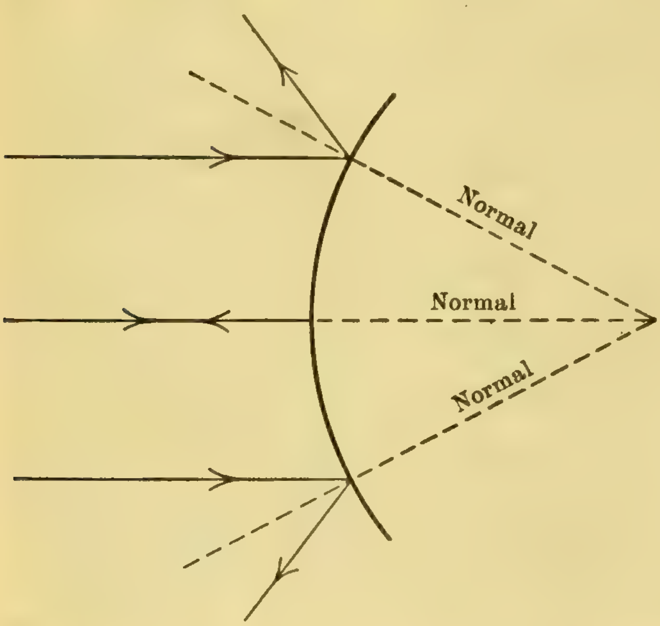


FIGURE 270. — Convex mirrors diverge light.

The stars are luminous bodies visible by their own light. The planets and the moon are visible because they reflect diffusely the light that falls on them from the sun. To an observer on another planet, the earth would appear to be a bright disk as the other planets do to us.

182. Regular Reflection from Curved Surfaces. — The law of reflection holds good for all surfaces, whether rough or smooth, plane or curved. When light falls on a convex mirror, it is reflected regularly but divergently (Figure 270). The radius of the arc is the normal and the incident and the reflected rays make equal angles with this normal. Since

the light is reflected regularly, an image of any body that sends light to the mirror is formed *behind the mirror.* The divergently reflected light only appears to come from this image, so the image is *virtual.* Convex mirrors are used on the fenders of automobiles because they show to the driver a small, erect image of a large area behind him (Figure 271).

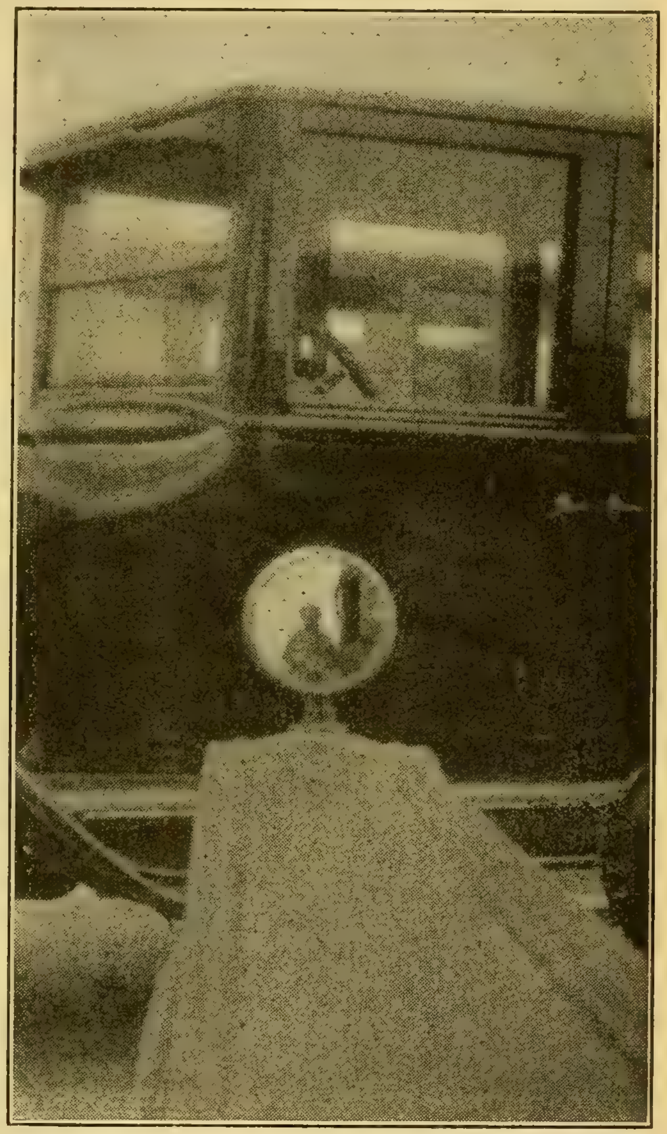


FIGURE 271. — Convex mirrors form small, erect, virtual images. Note the image of the man as formed by the mirror.

Concave mirrors, such as the polished bowl of a spoon, form various images according to the distance the source of light is from the mirror. Figure 272 shows that rays of light which fall on the mirror tend to be reflected regularly but convergently. The rays, however, may diverge if the object is too close to the mirror. The mirror, then, may form real, enlarged images; real, diminished images; or enlarged, virtual images. Concave shaving mir-

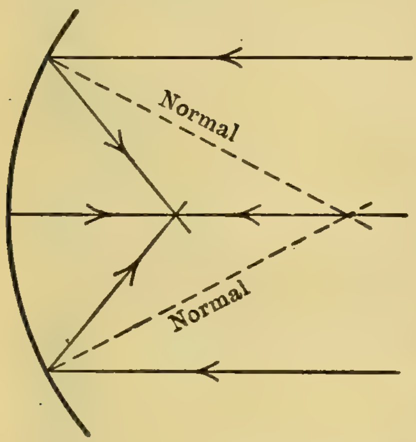
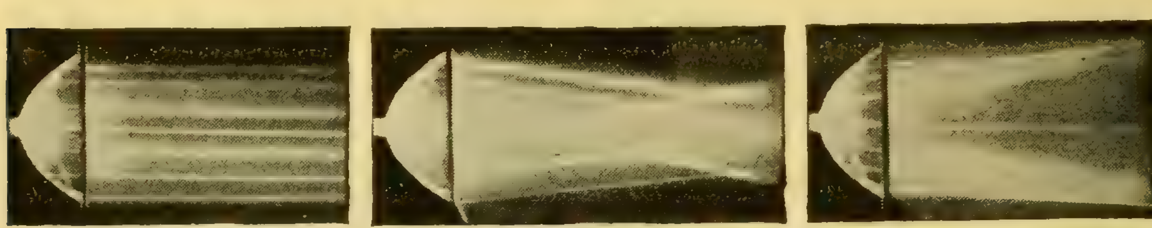


FIGURE 272. — Concave mirrors converge light.

rors form enlarged, erect, virtual images. Concave reflectors are used behind automobile lamps to concentrate the light that falls on them and send it forward on the road



Courtesy National Lamp Works of Gen. Elec. Co.

a *b* *c*

FIGURE 273. — The concave reflector sends all the light forward. (*a*) Lamp at focus; (*b*) lamp ahead of focus; (*c*) lamp back of focus.

(Figure 273). Large concave mirrors are used as the objectives in reflecting telescopes (Figure 274).

It should be noted that light which is *really* converged at a certain point forms a *real image* of the source of light at that point (Figure 275). Light that leaves a mirror divergently *appears* to center at a point and forms a *virtual image.*

QUESTIONS

1. Define reflection. Name five reflecting surfaces.

2. State the law of reflection. Illustrate it by a simple diagram.

3. State what is meant by regular reflection. Show how a number of parallel, oblique rays are reflected from a polished surface.

4. Describe a plane mirror image.

5. Why are plane mirror images virtual? Why are they reversed from right to left?

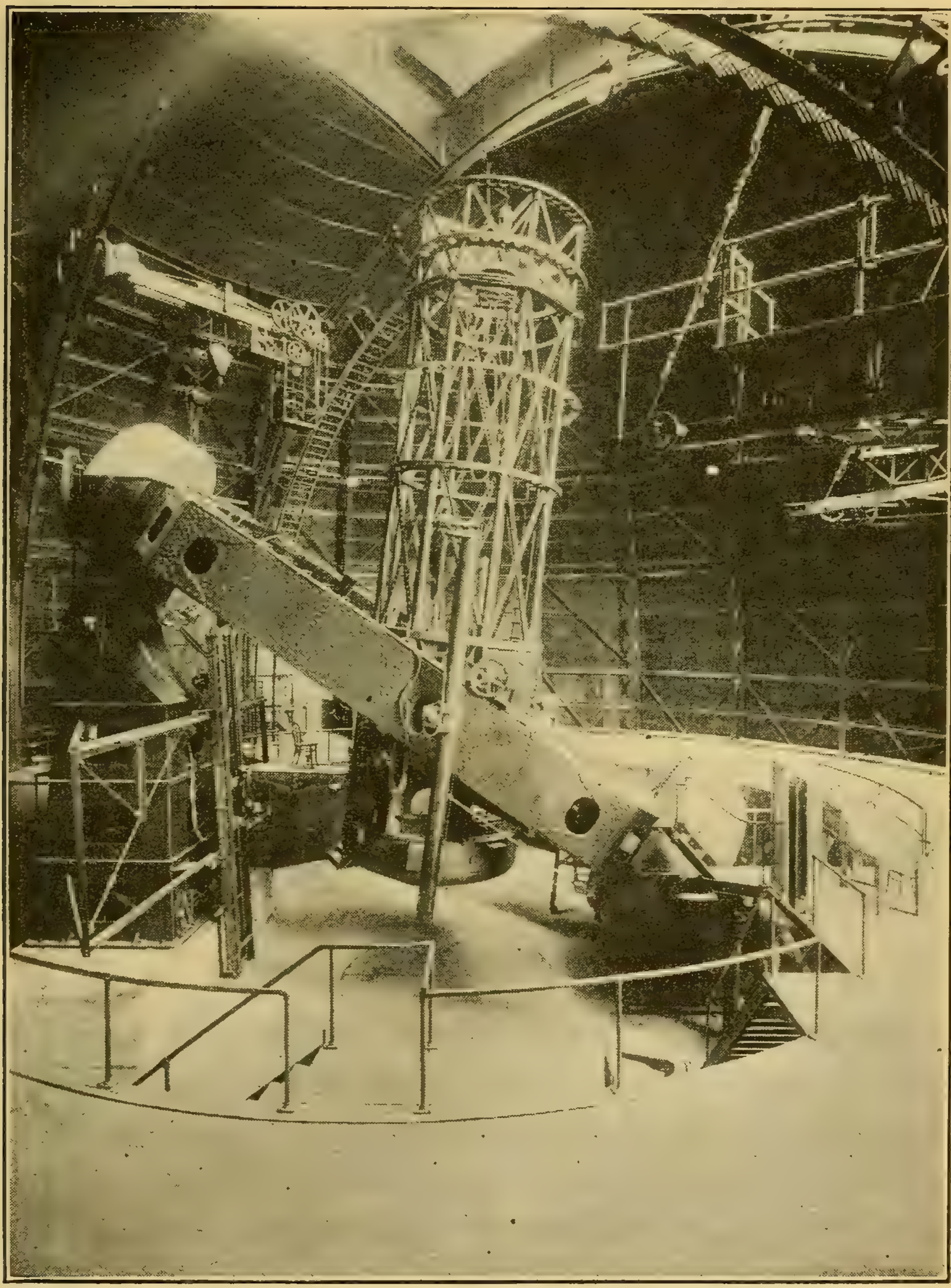
6. What is diffuse reflection? Illustrate by diagram the diffuse reflection of a number of parallel rays.

7. What is the importance of diffuse reflection ?

8. Show by diagram the result of parallel rays falling on a convex mirror.

9. Describe the image formed by a convex mirror such as is used on automobile fenders.

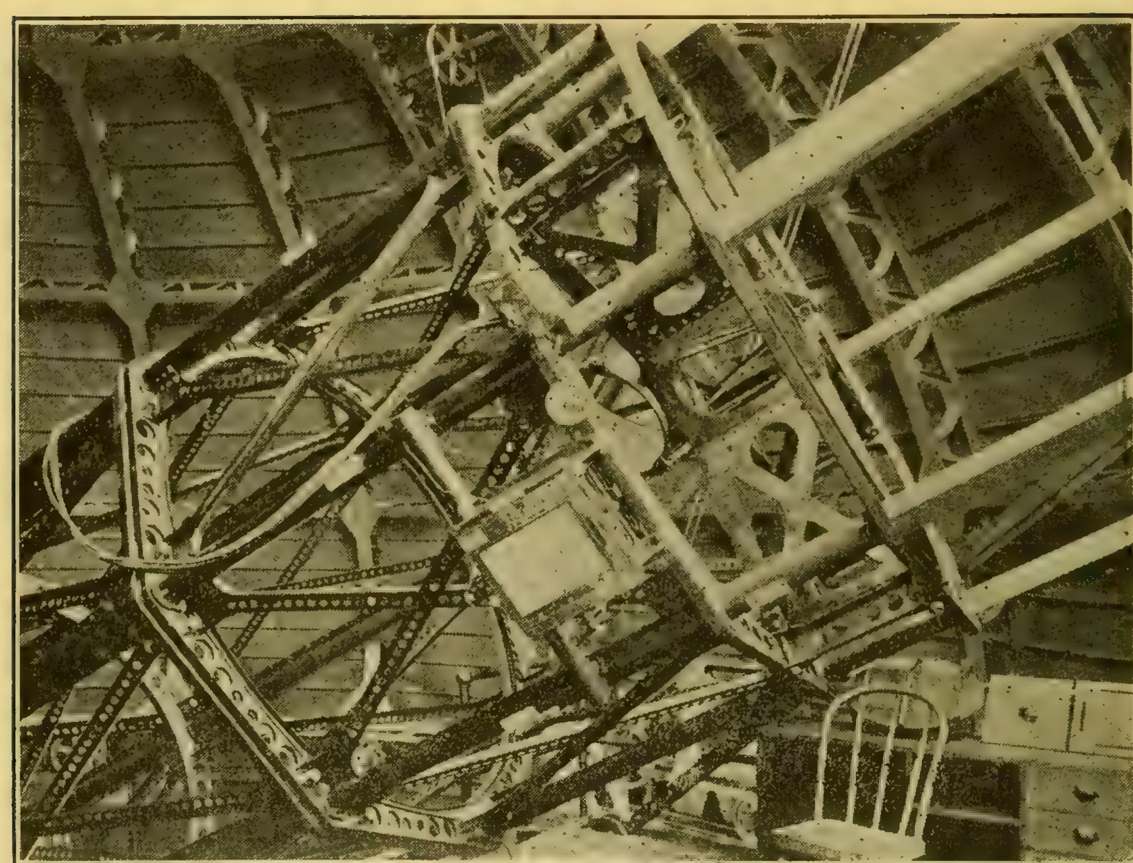
10. Show by diagram how a concave mirror reflects parallel rays of light.



Courtesy of Carnegie Institution, Washington, D. C.

FIGURE 274. — THE LARGEST REFLECTING TELESCOPE, MT. WILSON, CAL.

At the bottom is a 100-inch concave mirror. Light from the stars is reflected by this to form a real image near the top of the frame, where it may be photographed. By additional mirrors, the reflected light may be directed to eye pieces outside the frame.



Courtesy of Carnegie Institution, Washington, D. C.

FIGURE 275. — PHOTOGRAPHING AT MT. WILSON.

The inclined plane mirror within the frame (center) turns the starlight to a focus on the photographic plate seen clamped to the frame.

Refraction

133. Refraction. — Objects seen obliquely through glass or water are not where they seem to be (Figure 276). This is an apparent exception to the principle that light travels in straight lines. There is something about glass or water that changes the direction of light passing obliquely into them. A simple experiment will show the deviation of light from its course.

EXPERIMENT 79. — Fill a battery jar with water. Cover the jar with a cardboard in which a slit has been cut. Let a strong light from an arc lamp fall obliquely upon the water surface through the slit. The ray of light is seen to take a different direction in the water.

The bending of a ray of light as it enters a different medium obliquely is called refraction.

Although many cases of this bending of light escape our notice, we have all observed some examples of refraction. A spoon in a glass of water appears broken at the surface and distorted below the surface. A pole or an oar stuck into the water undergoes the same change in appearance. A stone seen through the water is not where it appears to be, because of refraction (Figure 277). A glass paperweight displaces the printing seen through it and any thick-walled bottle or jar bends the light passing through it, and thus distorts the appearance of objects seen through the walls.

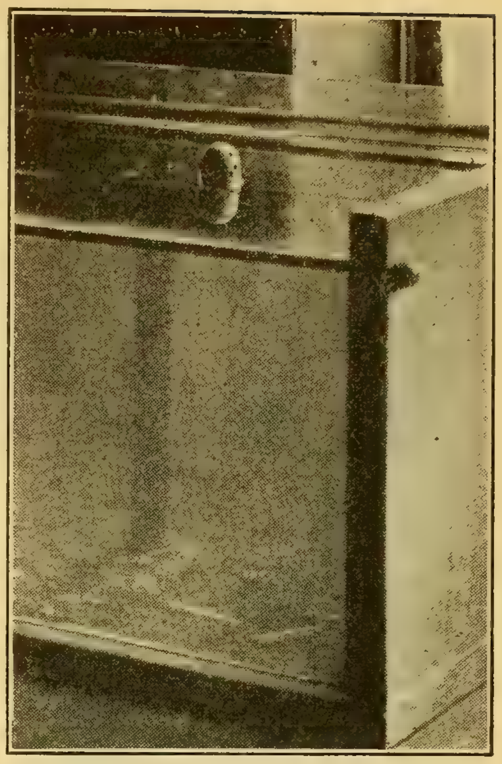


FIGURE 276. — The cap above the water is attached actually to the pipe below. Refraction causes them to appear separated.

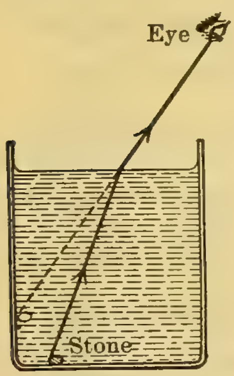


FIGURE 277.— Light from the stone is bent as it leaves the water surface obliquely. The stone appears above and beyond its actual position.

Refraction occurs whenever light goes into a substance having a different *optical density.* We shall see in the following experiment how the course of a ray of light can be estimated after refraction, *i.e.* in which direction the bending will take place as the light enters a denser or rarer medium.

EXPERIMENT 80. — An optical disk is a circle divided into degrees, upon which various optical devices may be mounted for study (Figure 278). On such a disk place a glass half cylinder and allow light from a narrow slit to fall obliquely upon the glass at the center of the diameter. The light is bent as it enters the glass

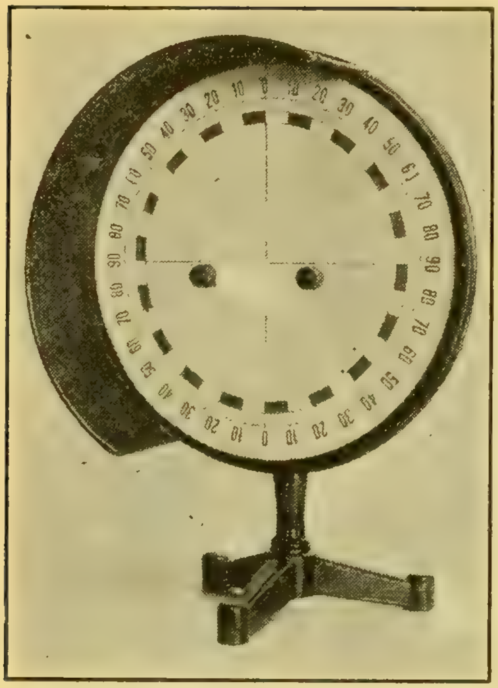


FIGURE 278. — Light entering the glass obliquely is bent nearer the normal.

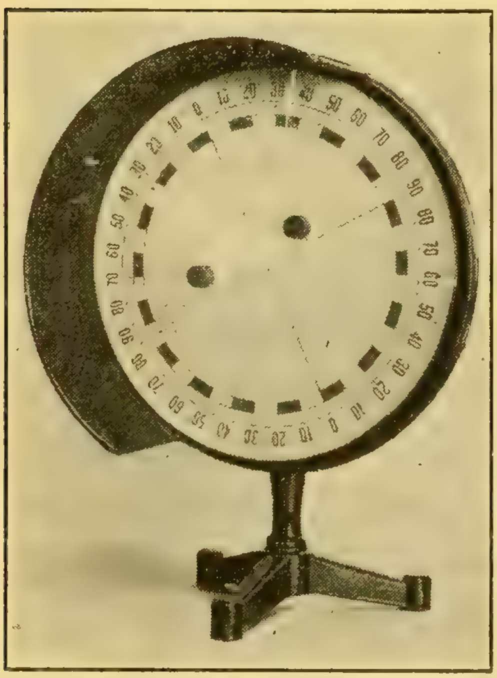


FIGURE 279. — Light is caused to strike the curved surface normally so there is no bending. Leaving the glass at the plane surface it is bent away from the normal. Note the reflected ray.

and proceeds in a new direction through the glass. *Does it bend toward or from the 0 line?* On leaving the glass, however, there is no refraction because the light strikes the air surface along a normal. Turn the disk so that the light may strike the curved edge of the glass and proceed along a radius to the center of the diameter (Figure 279). In this case the light is bent when it leaves the straight side of the half cylinder, for it falls upon this obliquely. *Does it bend toward or from the 0 line?* The light is not bent in either case at the curved surface of the glass, because it falls along a normal to that surface.

184. Laws of Refraction. — The results of the two cases of the preceding experiment show that when the light enters the denser medium, glass, it is turned into the glass at a steeper angle. The reverse is true when the light emerges from the glass into air. Let us state these results in a different way. Imagine a normal to be drawn perpendicular to the glass where the light strikes the glass. This is the 0–0 line on the optical disk. Then the light within the glass lies closer to this normal than the light in the air, no matter which way the light travels. *When light enters a denser medium*

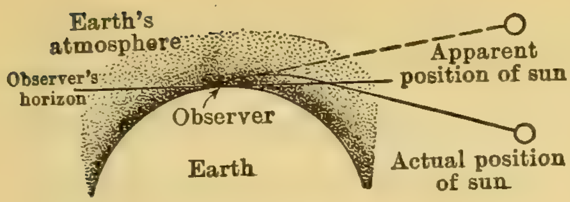


FIGURE 280. — Refraction by the earth's atmosphere causes the sun to be seen before it rises (exaggerated).

obliquely, it is refracted so as to pass nearer the normal; when light enters a rarer medium obliquely, it is bent farther from the normal. These statements are the *laws of refraction.*

It should be noted that the light always crosses the normal and that, until the light is actually perpendicular to the glass, no matter how small the angle of incidence is, the angle of refraction is still smaller if the light enters a denser medium. The term *density* refers to the *optical* rather than the physical density of substances. A few media are given here in the order of their optical density, the less dense first: vacuum, air, water, crown glass, flint glass, carbon disulphide, ruby, diamond. The air refracts light from the sun and the moon and thus causes these bodies to be visible longer than they otherwise would be (Figure 280).

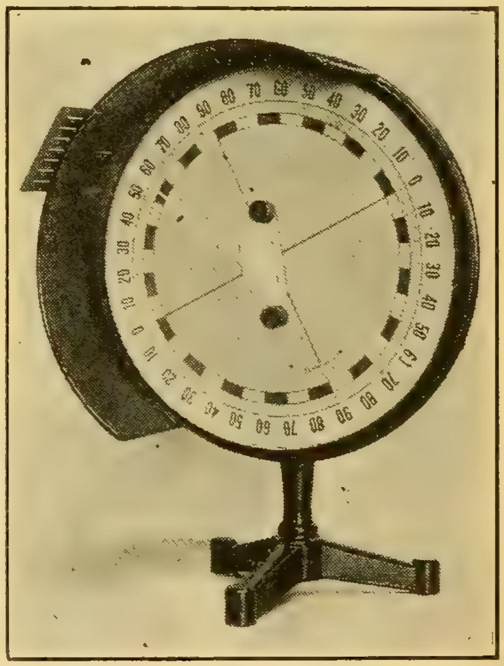


FIGURE 281. — Photograph of a ray of light passing through a parallel-sided glass plate.

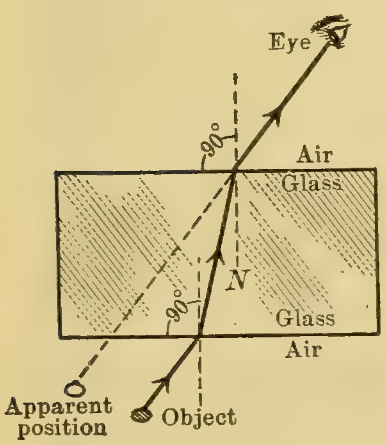


FIGURE 282. — Diagram of path of light shown in Figure 281.

185. Refraction through a Parallel-sided Glass Plate. — A rectangular glass plate is mounted so that light passing through a slit falls upon it obliquely (Figure 281). The light is seen

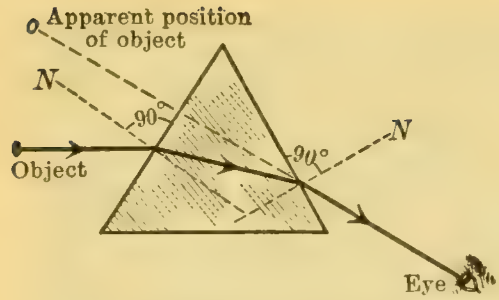


FIGURE 283. — A triangular glass prism usually bends the ray twice, both bends bringing the ray nearer the base.

to bend toward the normal on entering the glass, and to resume its original direction on leaving. The refraction due to the denser medium is reversed as the light reënters the rare medium, air. Objects seen through thick glass are not exactly where they appear to be (Figure 282).

186. Refraction through a Triangular Prism. — If a triangular glass prism is used as in Figure 283, the light on

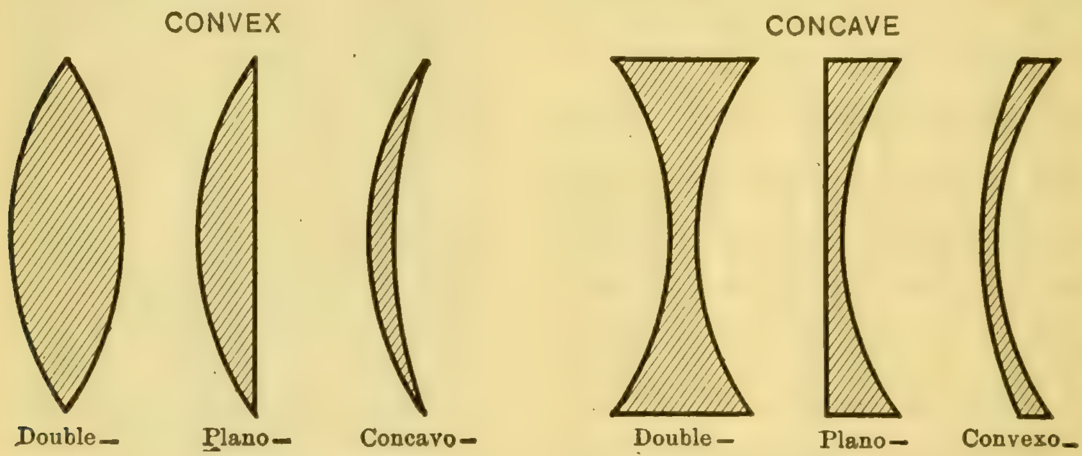


FIGURE 284. — Common forms of simple lenses.

entering the dense medium bends toward the normal, *N*. The light bends away from the second normal, *N*, as it leaves the prism on the other side. Both of these bends cause the ray to come closer to the base of the prism.

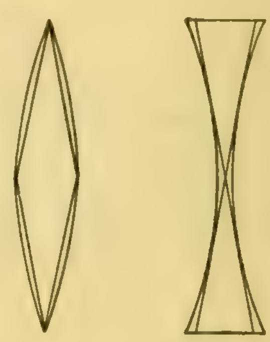


FIGURE 285. — Left, convex; right, concave.

187. Lenses. — Of great importance is the refractive effect of a transparent lens in the eye, which bends the light entering the eye until vision results when these bent rays form an image upon the retina. The ability of the eye to bend rays of light is not al-

ways what it should be. To add to this ability, or to subtract from it, lenses of glass are used. A lens is usually bounded by two spherical surfaces, and the common forms are shown in Figure 284. Convex lenses, which are thicker in the center than at the edges, are like two triangles placed base to base (Figure 285). Rays of light striking the upper triangle are bent down (§ 186), while rays striking the lower triangle are bent up. The resulting effect of convex lenses is to converge light, or tend to do so (Figure 286).

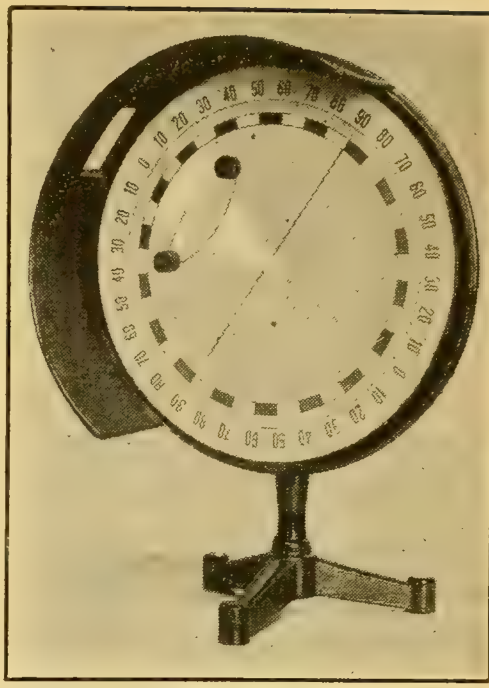


FIGURE 286. — The converging effect of the convex lens.

Concave lenses, which are thinnest at the center, act as triangles placed apex to apex, and therefore cause rays of light falling on them to diverge (Figure 287).

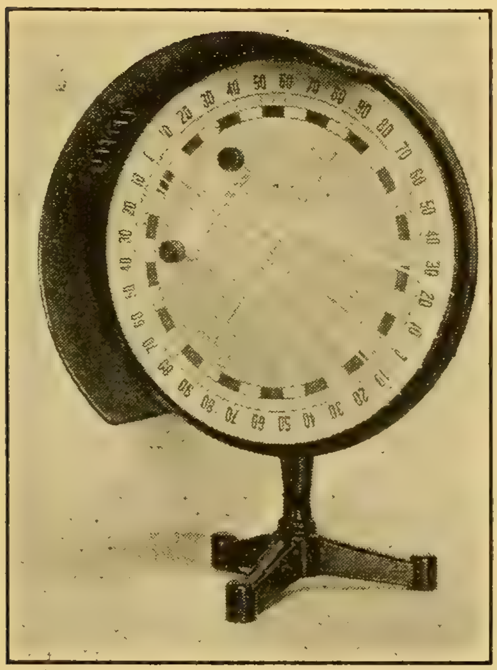


FIGURE 287. — The diverging effect of the concave lens.

Farsighted eyes that need greater refracting power are fitted with convex lenses. If the eye already has more bending power than it needs, the person is nearsighted and concave lenses are used.

More will be said about the formation of images by lenses in a later chapter, but enough has been said here to show that vision itself and the correction of de-

fects in vision depend upon refraction. By reflection, light reaches the eye from all non-luminous objects. By refraction, this reflected light is bent by the lens of the eye so as to form images that fall upon the retina and are transmitted to the brain.

QUESTIONS

1. Describe an experiment that shows the bending of light when it enters a different medium obliquely.

2. Define refraction. State the laws of refraction.

3. Show by diagram and describe the path of light through a parallel-sided plate. Locate on this diagram the source of light, the eye that receives the light, and the apparent position of the source of light.

4. Trace the path of light through a triangular prism of glass. Show the source of light, and the apparent position of the source as seen by an eye on the other side of the prism.

5. What are the two principal classes of lenses? What effect does each have on light?

SUMMARY

Vision occurs by light forming an image on the retina of the eye.

Light travels in straight lines as long as it does not change its medium.

Shadows are darkened spaces caused by the exclusion of light by opaque bodies. An **umbra** is caused by the entire exclusion of light from an area. A **penumbra** results from the partial exclusion of light from an area. **Eclipses** occur when either the earth or the moon casts a shadow on the other by shutting off the sun's light.

Reflection is the return of light into the medium of transmission when it falls on a different medium.

The Law of Reflection states that the angle of incidence equals the angle of reflection and lies in the same plane.

Regular reflection occurs when light falls upon a polished sur-

face. Images are formed by regular reflection. **These images, formed by a plane mirror**, are erect, virtual, the same size as the object, as far perpendicularly behind the mirror as the object is in front of it, and are laterally reversed.

Diffuse reflection results from irregularities on the reflecting surface. Light is scattered in all directions from these irregularities. Most common objects are diffuse reflectors and are therefore visible. Diffusely reflected light illuminates areas that would otherwise remain dark.

Curved surfaces may reflect light regularly.

Convex mirrors form small, erect, virtual images behind the mirror. **Concave mirrors** may form real, inverted images, which may be either larger, smaller, or the same size as the object; or large, erect, virtual images may be formed behind the mirror.

Refraction is the bending of the course of light when the light falls obliquely upon a different optical medium.

The Law of Refraction states that on entering a **denser** medium obliquely, light is bent **toward** the normal. On entering a **rarer** medium obliquely, the light is bent **away** from the normal.

EXERCISES

1. Name four men who have added to the present knowledge of light. What contribution to this knowledge was made by each?

2. How has the knowledge of light aided other sciences? Give examples.

3. Compare the shadow cast by a single lamp with that thrown by a group of lamps.

4. Why are the nights brighter when the snow is on the ground?

5. Are all parts of the room you are in directly illuminated by either sunlight or artificial light? Would your handkerchief be visible in any part of the room? Why?

6. Should the basement of your house be painted black inside, or whitewashed? Why?

7. Should book paper, wall paper, and paint for interiors be rough or smooth? Why?

8. A white house has a new, shiny metal roof. Is the wall or the roof more easily seen at a distance? Why?

9. Why can you not read print from a page held in front of a mirror? What kind of writing can you read in a mirror?

10. A clock, seen in a mirror, at various times appears to indicate the following hours: 4 o'clock, 6 o'clock, 8 o'clock, 11 o'clock, and 7.30. What is the actual time in each case?

11. How tall a vertical mirror do you need to be able to see your entire figure? If you stood farther away, could you use a smaller one for the same purpose?

12. If you stand before a mirror and move toward the mirror, which way will your image move? If you move to your left, which way will it move?

13. If you stand a pin in a vertical position and incline a mirror toward it at an angle of 45°, what position will the image of the pin appear to take? Illustrate by diagram.

14. What is the difference between a white, a black, a gray, and a red surface?

15. Show how a straight post, standing vertically in the water, appears to an observer at one side.

16. A coin at the bottom of an opaque pitcher is invisible when you look obliquely into the pitcher, but becomes visible when the pitcher is filled with water. Explain.

17. Show by diagram the real and the apparent position of a stone seen obliquely through the water.

18. Air over fires or radiators is less dense than the surrounding air. Why are so-called heat waves visible at these places? (These are *not* the waves of radiant heat.)

19. Why does a piece of glass used as a mirror form two images?

20. Although the moon can often be seen by day, lunar eclipses never are. Explain.

21. The earth's shadow in space has three dimensions, while your shadow on the sidewalk has only two. Explain.

22. The sun appears to rise earlier than it really does. Explain.

CHAPTER XV

LIGHT WAVES AND COLOR

NEARLY all the things we know about physics to-day are the results of the attempts and failures of early philosophers to explain natural happenings. Experiment, theory, fantastic guesses, and careful reasoning have all played a part in developing our present knowledge. This is particularly true of light because of the difficulties attending its study.

188. Velocity of Light. — The ancients believed that light required no time at all to go from place to place. They held this belief because the time taken by light to travel any *earthly* distance is so brief that ordinary methods would fail to detect it. Light seemed to them to be instantaneous.

Galileo, who seems to have taken less on faith than his predecessors, did attempt to determine whether light has velocity, but he failed to obtain a positive answer. After the time of Galileo the telescope came into use and with the great distances of the heavenly bodies to work upon, the velocity of light was ascertained.

189. Römer's Method of Finding the Velocity of Light. — The first reliable figures for the velocity of light were obtained by a Danish astronomer, Römer. Frequent observation had established the fact that Jupiter's inner satellite was eclipsed, *i.e.* darkened by entering Jupiter's shadow, on an average of once every $42\frac{1}{2}$ hours (Figure 288). Let us assume the earth (E^1) and Jupiter (J^1) to be on the

same side of the sun at a certain time. They will both revolve around the sun, the earth making about 12 revolutions to one of Jupiter. In a little more than half a year, the earth (E^2) will be on the side of the sun away from Jupiter (J^2). During this time the interval between eclipses has been increasing as the earth gets farther from Jupiter. From then on, however, the eclipses occur at shorter intervals until the two planets are again on the same side of the sun. The difference between the longest and shortest interval is about 1000 seconds ($16\frac{1}{2}$ min.). Römer explained the lengthening interval, as the earth moved away from Jupiter, as being due to the longer distance that the light had to travel to reach the earth. That is, the reappearance of the satellite from the shadow would not be visible at the calculated time, because light must travel farther to reach an observer on the earth. As the earth approaches Jupiter, light from the satellite travels a shorter distance to reach the earth, and the interval between eclipses is decreased. Since the increase in distance is the diameter of the earth's orbit, roughly 186,000,000 miles, and the additional time required for light to travel this distance is 1000 seconds, we see that light must travel with a velocity of 186,000 miles per second.

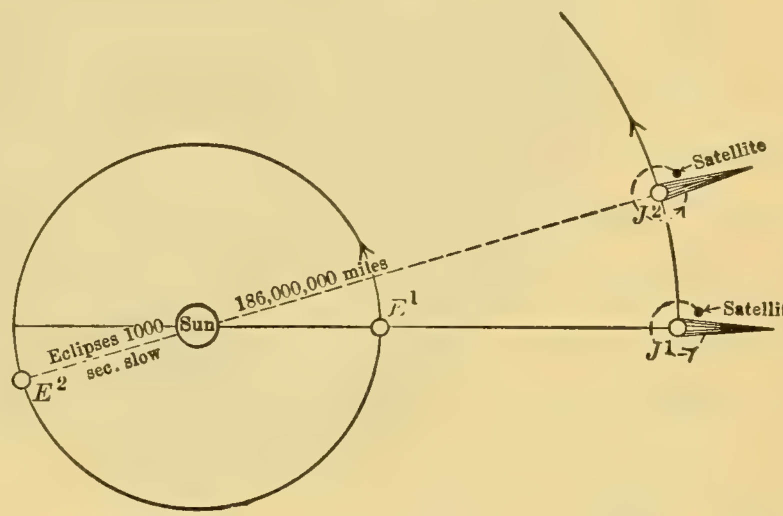


FIGURE 288. — RÖMER'S METHOD OF DETERMINING THE VELOCITY OF LIGHT.

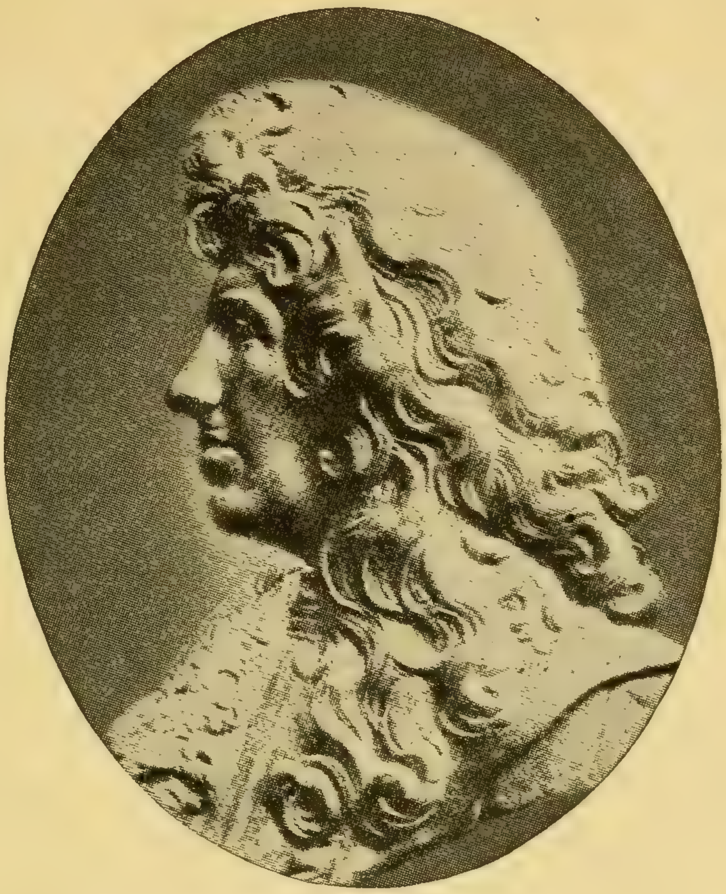
Römer's ingenious explanation was too advanced for his

fellow-scientists and was accordingly neglected for fifty years after his death. His determinations, slightly corrected in detail, have been verified in general, so that the figures given by Michelson are 186,360 miles per second. The mind can form little notion of this enormous speed. If light could be reflected by mirrors rightly placed, it would go $7\frac{1}{2}$ times around the earth in one second. So distant are the stars from us, however, that we see the nearest one by light that left the star 4 years ago, while in the case of the more remote stars, light emitted thousands of years ago has not yet reached us.

190. Nature of Light. — Without any investigation of the subject, the nature of light was thought to be a power of the eye, that is, the eye grasped objects by some invisible arm and rendered an image of them. This belief held until the rise of the great group of scientists that in the seventeenth century made the beginnings of modern physics. Even then a divergence of theory left the question as to what light really is in doubt for a still longer period.

It seemed to Newton and some of his associates that all the phenomena of light could be explained by considering light to be an emission of *corpuscles* from luminous bodies. These tiny projectiles would travel in straight lines, would be reflected regularly from smooth surfaces, and in general would behave very much as light does. The refraction of light, however, could be explained only by assuming that light travels *faster* in dense substances than in rare ones. When experiment proved that light travels faster in rare substances, the emission theory was abandoned.

Huyghens, a Dutch contemporary of Newton and a man of great ability, put forth the theory that light is a kind of wave motion like sound. The first objection to be met in



Christian Huygens (1629–1695) was a Dutch contemporary of Newton. Outside of his work in mathematics for which he became internationally famous, he is best known for his wave theory of light. This theory, maintained against Newton's authority, is universally accepted to-day, although it was not popular until long after Huygens' death. Huygens named and described the "aether" or the medium through which light waves are thought to travel. He discovered the polarization of light, made astronomical telescopes, and achromatic lenses. In another field he applied the isochronous (equal time) vibrations of a pendulum to timepieces. In connection with this last invention, he measured the value of gravity's acceleration and its variation at different parts of the earth's surface, but failed to realize the general application of the law of universal gravitation which Newton was expounding in England.

establishing this theory was the fact that light travels where there is no known matter. To overcome this objection, Huyghens assumed a new medium that he called *ether*. The properties of this ether were that it occupied all space, including that between the molecules of all matter; that it was weightless, elastic, and possessed of no characteristics that would permit its detection. Upon this assumed substance, Huyghens built the *wave* theory of light, a theory that so far has satisfactorily explained most of the phenomena of light.

Newton turned away from this theory because of a second objection: sound, a known wave motion, passed readily around corners and did not maintain a straight-line motion. Light, he thought, could not be a wave because it persisted in traveling in straight lines only. Experiment showed that very short sound waves travel in straight lines and that sound waves as short as light waves would travel in no other manner. This overcame the second serious objection to the wave theory and the theory is to-day universally accepted.

Light is, then, a series of waves which pass through a substance called ether, and which are capable of producing vision. Observation has shown that these waves are *transverse,* meaning that the disturbance in the ether is perpendicular to the forward motion of the wave itself. An idea of the meaning of the word *transverse* may be obtained from the study of a waving flag. A ripple runs from one end of the flag to the other, but each particle of cloth moves only from side to side — transverse, that is, crosswise to the motion of the wave itself. Transverse waves are easily set up in a rope attached at one end and shaken at the other (Figure 289).

191. Electromagnetic Vibrations. — Waves are the result of vibrations. The number of waves per second, or frequency of vibration, can be determined by dividing the velocity of light by the length of the wave. The longest wave length of visible light is about eight ten-thousandths of a millimeter (0.0008 mm), while the shortest wave that can be perceived by the eye is about 0.0004 mm long. Dividing the very great velocity by the very small wave

FIGURE 289. — TRANSVERSE WAVES IN A ROPE.

The rope moves up and down, but the wave impulse travels from the hand to the post.

length brings us to the conclusion that the frequency of the vibrations that produce light waves must range between about 400 trillions (millions of millions) and 750 trillions of vibrations per second. Of course such frequent vibrations can come only from very small bodies. These bodies are electrons (§ 279), parts of atoms which are in rapid motion about the center of the atom. Changing the orbits of rotation of these electrons is thought to set up a series of waves in ether, known as *electromagnetic* waves.

192. Other Electromagnetic Waves. — It is of interest to note that relatively few of the waves emitted by electrons are able to excite the eye and thus enable us to see. About one sixtieth of these waves are able to produce vision, while the larger portion of them must be studied by some other effect that they produce (Figure 290). Among the longest of these invisible waves are those that carry messages in wireless telegraphy (Chapter XXXVI), and are called

Hertzian waves, after their discoverer. Shorter than the Hertzian waves are the *infra-red* or *heat* waves. Next in order are the *light* waves, which have been noted above. The *ultra-violet* waves are shorter than light waves and do not affect the eye. Their presence can be detected by a photographic plate upon which they produce the same effect as light waves do. *X-rays,* which appear to be very short waves, have the peculiar property of passing through sub-

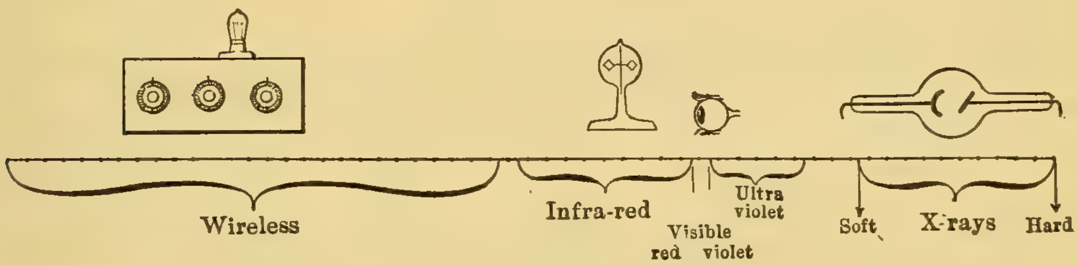


FIGURE 290. — CHART OF ETHER WAVES (AFTER MILLIKAN).

The visible portion of the electromagnetic waves lies between red and violet. By far the larger portion of ether waves are too long or too short to affect the eye, and must be detected by other means. The wave length at each dot from left to right is half that at the dot before.

stances that are opaque to longer waves. X-rays are not able to excite the optic nerve, but, if allowed to fall on certain fluorescent substances, they cause such substances to emit waves that do affect the eye and permit vision.

The five groups of waves mentioned here differ in length and in the effects that they produce because of this difference in length. The eye is limited in its ability to respond to waves that enter it, hence the greater portion by far of the ether waves is invisible.

A survey of the preceding paragraphs shows that rapidly vibrating electrons emit waves that pass through ether at a speed of 186,000 miles per second. Since the vibrations are of all frequencies, the waves are of all lengths. Waves that range between the lengths of 0.0004 mm and 0.0008 mm

are waves of visible light. All other waves are invisible and are detected by other effects that they produce.

QUESTIONS

1. What is the velocity of light? By whom was the velocity of light first measured?

2. Does light or sound have the greater velocity? Which velocity would it be easier to determine? Why?

3. What have you observed to make you believe that the velocity of light is greater than that of sound?

4. What is meant by a *wave motion?* What forms of wave motion have you seen?

5. What man first pointed out the relation between light and wave motion?

6. What objections were raised to the wave theory of light? How were these objections overcome?

7. What difference exists between light waves and heat waves?

8. The eye and a radio receiving set both respond to electromagnetic waves. Which responds to a longer wave? Which requires a larger amount of energy for detection?

193. Dispersion. — We have seen above that waves produce different effects according to their length. Let us now sort out the light waves of different lengths and determine whether the long light waves produce the same effect as the short ones. One method of sorting the waves according to their length is used in the following experiment.

EXPERIMENT 81. — Stand a triangular glass prism on one end and let light from the sun or from a stereopticon fall through a narrow slit upon the prism [1] (Figure 291). The light emerges from the prism along

[1] The best way of securing a spectrum with a stereopticon is to place in the slide holder a sheet of metal the size of a lantern slide, having a slit $\frac{1}{8}$ to $\frac{3}{16}$ in across. Focus this slit on the screen where the spectrum is to be shown. Then mount the prism in front of the objective in the path of the light from the slit, and turn the lantern until the spectrum falls on the screen. A top view is seen in Figure 292.

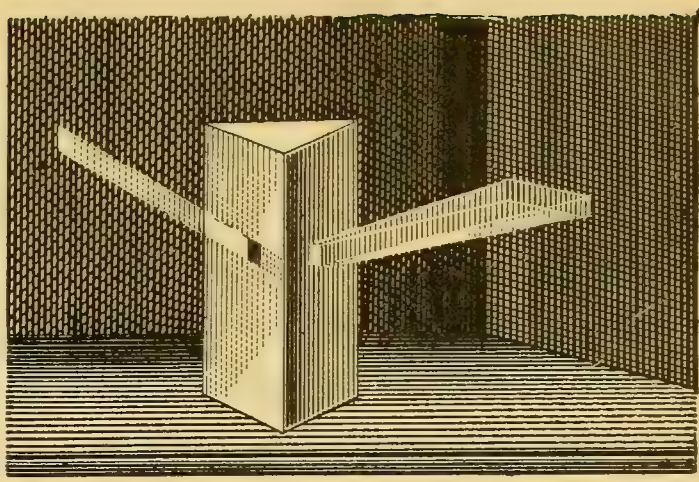


FIGURE 291. — White light passing through a triangular prism is spread out (dispersed) into its separate colors.

a new path and is much spread out. Allow this light to fall upon a white screen and an image of the slit in all the colors will appear upon the screen. This colored band is called a *spectrum*. *Has the red or the blue been refracted more? What colors can you detect in the spectrum?*

The wave length of the light in every part of the spectrum has been carefully measured by simple means. The wave length in each of several different parts of the spectrum is shown in the table:

Deepest red	0.0000324 in.	0.00081 mm
Red	0.000026 in.	0.00065 mm
Orange	0.0000233 in.	0.000583 mm
Yellow	0.000022 in.	0.00055 mm
Green	0.0000205 in.	0.00051 mm
Blue	0.000018 in.	0.00045 mm
Violet	0.000016 in.	0.0004 mm
Deepest violet	0.0000144 in.	0.00036 mm

We see that the color of light, then, depends simply upon the length of the wave producing the light. Red is seen to have the longest wave, violet the shortest wave, and green intermediate between the two.

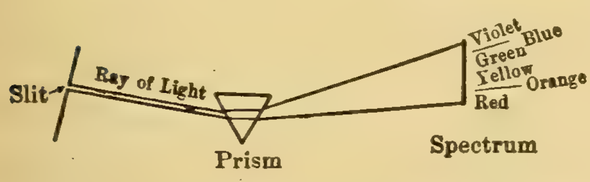


FIGURE 292. — TOP VIEW OF DISPERSION EXPERIMENT.

White light from the sun or the arc lamp is white, because it is composed of a proper proportion of all the visible wave lengths. White light, or any other composite light, may be separated into

the colors that make it by sending the light through a triangular prism, or any transparent substance having non-parallel sides. The separation of light into its component colors is known as *dispersion.* Drops of water, cut glass, diamonds, etc., form *rainbows, i.e.* spectra that result from dispersion by the non-parallel sides of the transparent bodies.

194. Color. — To get a proper understanding of color we must consider three aspects of the subject: the waves that produce the different color sensations, the eye that receives these sensations, and the brain that interprets and identifies them. Concerning the waves that produce color sensations, we may say that there are an infinite number of different wave lengths, each representing a different color. But the eye is thought to be able to respond only to three (or perhaps four) primary color sensations, — usually given as red, green, and blue. The brain is able to recognize and identify a large number of colors according to the training the person has had in distinguishing combinations of these color sensations. An artist or a mosaic worker can identify hundreds of distinct colors, while a savage could perhaps separate only a few.

From a physical standpoint, there ought to be as many colors as there are different wave lengths — an infinitely large number. According to this theory, the eye can recognize only three groups of wave lengths, because it can respond only to the stimulus of three kinds of waves, red, green, and blue. But the brain recognizes these three primary sensations and a large number of mixtures of them, so to the brain there are as many colors as it can tell apart.

When the eye receives all wave lengths in the right proportion, the brain says "white." Purple is identified by the brain, when a mixture of blue and red is received by the

eye. Other shades and tints, as pink, brown, lavender, and orange, are mixtures of two or more of the three primary colors in varying proportions. Some colors, such as orange and yellow, may be either pure or compound colors. These colors in the spectrum are pure, *i.e.* they are formed by waves of one length. On the other hand, both orange and yellow can be made by combining red and green in different proportions and hence cannot be designated as primary colors.

195. Color of Opaque Objects. — We are familiar with the fact that some cloth seems to have a different color under artificial light. This leads us to the belief that color is not something which exists in the object, but is a *sensation* produced in the brain by light sent from the object to the eye. A red rose seen by white light appears red because only one of all the waves that fall on the rose (the red) is reflected. The rose absorbs the remaining waves, because some peculiarity in its surface renders it unable to reflect the blue and the green. If the rose is placed in the blue portion of the spectrum, the rose can reflect none of the light that falls upon it. Since no light now comes to the eye from the rose, the brain is conscious of a space from which it receives no light, and the name *black* is applied to this lightless area. Placed in the red portion of the spectrum, the rose is again able to reflect the same kind of light as it did when white light fell on it, so it again seems red.

In artificial light, the longer waves predominate, so reds and oranges seen by artificial light appear to be nearly the same color as in daylight. Blues and greens are much changed, however; a blue serge suit appears to be black in lamplight. *Colored opaque bodies are selective in their reflection of light and their color is determined by the wave length, or lengths, that they reflect to the eye.*

Transparent bodies, as colored windows, absorb some waves and transmit others. The color of the transparent substance is judged by the wave length of the light it *transmits.*

196. Mixing Pigments. — When we have spoken about various colors being the result of mixing light, the question naturally arises as to the result to be obtained by mixing paints or other coloring matter. A certain paint is called yellow because it reflects the wave length that corresponds to yellow light, but the ordinary yellow paint is impure and reflects a considerable amount of green, also. Another paint is called blue because it reflects blue principally. It reflects some green also, but absorbs all remaining waves. If these two paints are mixed, the yellow absorbs the blue waves, while the blue absorbs the yellow. The green, which is reflected by each, is not absorbed but is reflected to the eye, and the mixture is called green. Mixing yellow and blue *light* results in the formation of white again.

197. Colored Films. — When a drop of oil spreads over water, a number of colors can be seen. Soap bubbles give similar color effects. A part of the light falling on the thin film of oil is reflected from the top of the film, while some is reflected from the under side of the film. At any place where the film is one fourth of the wave length of yellow light in thickness, the light from the under side will be reflected in time to join the light from the top just one full wave behind. The two reflections are in step, or *in phase,* and yellow is seen at this place, because of the reënforcement of the two waves. Other colors are formed wherever the film is one fourth, or any odd quarter, of the wave length of that light, in thickness. Where the film is half the wave length of any color in thickness, the reflection from the under side

reaches the top just a half step behind. One series of waves entirely neutralizes the other series and the color is destroyed. The complement of the destroyed color will appear at this spot. The destruction of waves by their getting out of step, or phase, is termed *interference.* The wave length of light of any color can be determined by finding the thinnest film that will cause reënforcement of that color. The wave length will be four times the thickness of this film.

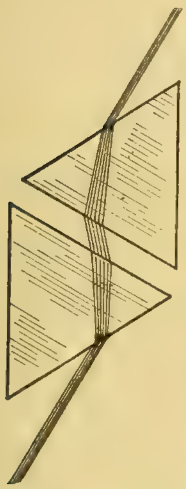


FIGURE 294. — Light dispersed by one prism is recombined by the second.

Interference is well illustrated by letting light from a sodium flame fall upon two glass plates, so clamped together as to leave a narrow space between them at the bottom. The wedge shown in Figure 293 is exaggerated in thickness to show the separation. Yellow light from the flame is destroyed by interference at various places on the plate, and a black band is caused where interference takes place.

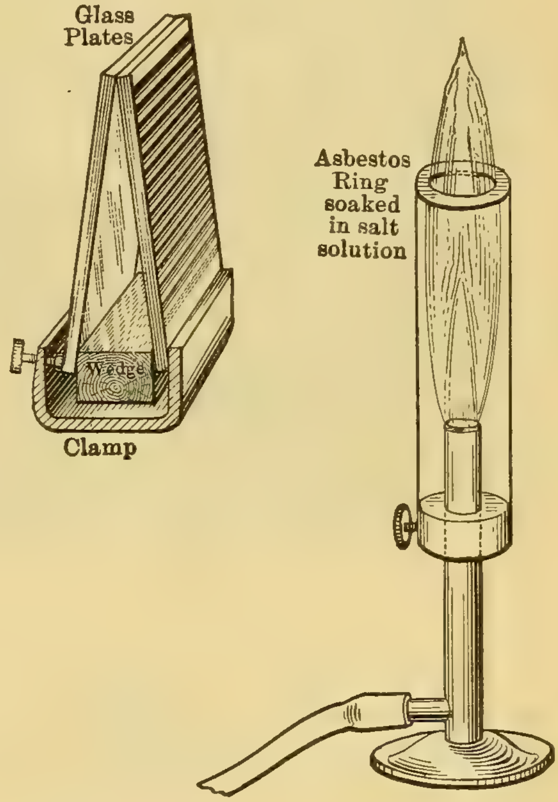


FIGURE 293. — The light and dark bands on the glass plate show alternate reënforcements and interferences of yellow light from the sodium flame. Waves are reflected from the adjacent glass surfaces either in step (reenforcement: yellow) or out of step (interference: black).

198. Synthesis of White Light. — We have seen that white light may be analyzed by passing it through a trian-

gular prism. A spectrum made up of lights of all wave lengths results from this dispersion. Now let us send the dispersed light through a reversed prism (Figure 294), and thus cause the different colors to overlap. The spot covered by the recombined lights is white. A convex lens may be used to focus the different waves on the same area, but a preferable method is to illuminate the same area by primary waves from different sources. In this latter method three openings fitted with adjustable diaphragms are covered respectively by red, green, and blue glass (Figure 295). A strong light is sent through these openings and, by movable lenses, the circular colored spots that fall upon the screen may be made to overlap to any desired extent. By adjusting the diaphragms so as to transmit the right amount of each light, we can make *white* by overlapping the three colored spots (Figure 296).

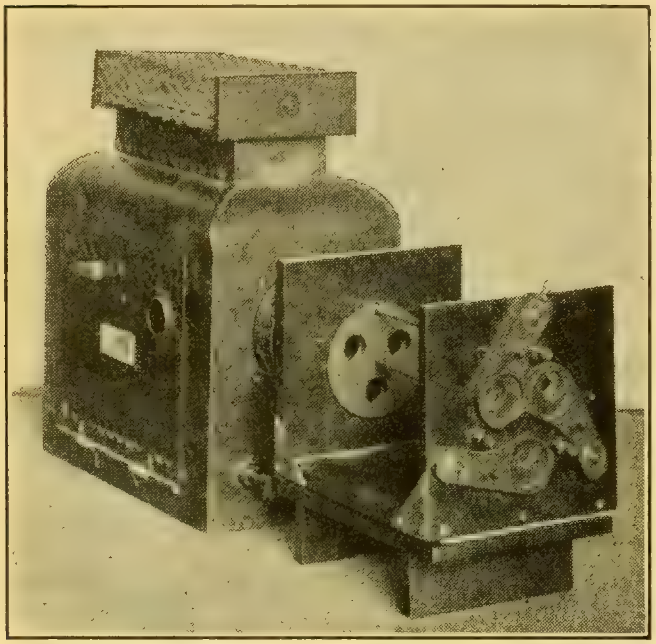


FIGURE 295. — VON NARDROFF COLOR MIXER.

Red, green, and blue glasses back of the three openings form colored spots on the screen. These may be combined by moving the lenses in front of the openings.

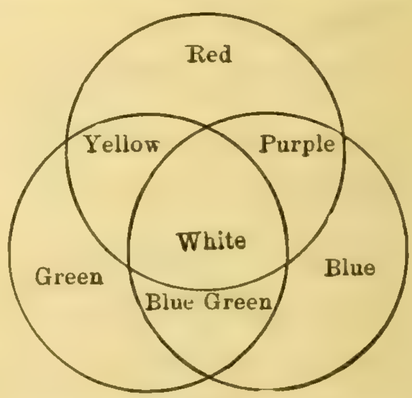


FIGURE 296. — Color resulting from causing the spots of light from the color mixer to overlap.

199. Other Combinations of Primary Colors. — Under proper conditions, all different shades may be

obtained by the combining of the primary wave lengths. Red and green form yellow when they are superimposed. Blue and green make an intermediate bluish green that is the *complement* of red, since it makes white when combined with red. Red and blue lights combine to form purple, the complement of green. Dark shades, as brown, olive green, slate, etc., are the result of spreading a mixture of lights over a large area, *i.e.* illuminating the area weakly.

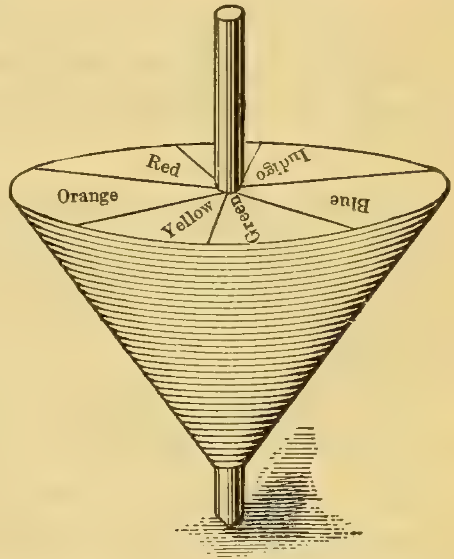


FIGURE 297. — COLOR TOP.

The rapid motion of the top causes the primary colors to blend on the retina of the eye, producing the sensation of white.

The results of the above combinations may be approximated by the use of a *color top* (Figure 297). On the upper surface of the top are placed various combinations of colored sectors that show, while spinning, the results of the color combinations.

200. Color Fatigue. — A red ribbon, seen in a strong light, stimulates and soon fatigues the nerve filaments that respond to red. If, after looking at the red, one looks at a white surface, the brain obtains the sensation of bluish green — the complement of red. The nerve filaments responding to red are tired by the recent stimulation of the red ribbon, so the strongest impression of the white light is carried to the brain by the filaments that respond to blue and to green. In a similar way, the complement of any color will appear on a white background after the color has been viewed steadily in a strong light for a minute or so. The predominance of green in nature has accustomed our eyes to stand this color without undue stimulation. Red,

however, acts first as a pleasing optical stimulant and then as an irritant, so it should be sparingly used in dress and decoration.

QUESTIONS

1. What difference exists between the lights that we call red and green? What colors are commonly named in the spectrum of white light?

2. Do other colors besides those named as primary exist in white light? What is the physical difference between one color and another?

3. To how many color stimuli is the eye supposed to be able to respond?

4. How many colors, shades, and tints do you know by name and by sight? Is your ability to distinguish these the result of good eyesight, or of education and training?

5. Why do things look different under artificial light than in the sunlight?

6. Why is one piece of cloth said to be blue, while another is green? Is the color a property of the cloth, or a sensation produced in the brain?

7. What is the approximate relation between the lengths of the red and the violet waves? How many wave lengths lie between these limits?

8. Is the same result obtained by mixing lights as is obtained by mixing paints or other pigments? Give an example.

9. Distinguish between dispersion of light and diffusion of light.

10. What effect upon the eye is produced by looking intently at a red object? What color fatigues the eye least? Why?

SUMMARY

The velocity of light is 186,000 miles, or about 300,000 kilometers per second.

Light is believed to be a **series of waves** that originate from the motions of electrons and that move through an assumed medium called **ether.**

Light waves are **transverse**, and must be more than 0.0004 and

less than 0.0008 millimeter in length. **Heat waves** and **Hertzian waves** are longer ether waves. Waves shorter than light waves may be **ultra-violet waves or X-rays.**

White light is a combination in proper proportion of all the different visible wave lengths. **White light may be separated** into its component parts by passing the light through a triangular glass prism. The separation of a light into its component parts is **dispersion.**

Each separate wave length represents a different **color.** The eye responds to only three primary color sensations, red, green, and blue. All other color sensations result from a mixture of wave lengths exciting the eye simultaneously. Distinguishing different colors is largely a matter of training in associating a proper color word with a given sensation.

Opaque objects reflect differently wave lengths of light which fall upon them. Some objects reflect practically all of the different wave lengths equally and are called **white.** Some objects absorb practically all of every wave length that falls upon them and are called **black.** Some objects absorb some wave lengths and reflect one or more wave lengths. These reflected wave lengths determine the color of the object.

Transparent objects may absorb certain waves and transmit others; their color is determined by the waves they transmit.

Mixing colored paints or pigments of any sort does not give the same effect as mixing lights, since the paints are able to reflect only those waves that have failed to be absorbed by the mixture.

Light waves may interfere with each other and produce a lightless area, or they may reënforce each other and form an area whose color is that of the reënforced wave. This is strong evidence for the wave theory.

EXERCISES

1. Give the steps and the reasoning involved in the first determination of the velocity of light. Use a diagram.

2. What is meant by the term *ether?* What relation does ether have to light?

3. What is the theory of light put forth by Huyghens? Why is the theory accepted to-day?

4. Light waves are thought to be transverse and sound waves to be longitudinal. What is the difference in these types of wave?

5. Name five kinds of electromagnetic waves in ether. How do the light waves differ from the others?

6. What difference exists between light waves themselves? Between what limits must these differences lie?

7. Describe an experiment by which the dispersion of light can be shown. What is the visible result of dispersion?

8. What is a spectrum? Describe the spectrum of white light.

9. What is the physical difference between the different parts of the white light spectrum? Give three examples of this.

10. Explain how the following color sensations are produced: red, white, green, yellow, blue, purple.

11. A color top has its upper surface painted in sectors of the different spectrum colors. What appearance should the top have while spinning? Explain.

12. A single prism disperses light and forms a spectrum, but a second prism, placed opposite to the first, recombines the dispersed light. What color is the light emerging from the second prism?

13. A spot of red light and one of blue and one of green are made to overlap each other partly. What will be the appearance of the area where all three overlap? Where red and green overlap? Where red and blue overlap?

14. Show how white, red, purple, and black surfaces differ in their ability to reflect light and to absorb light.

15. Most colors are impure, that is, the colored surfaces reflect other waves than they appear to do. Assuming that you have a rose which is pure red, how will it appear in the various parts of the white light spectrum? Explain.

16. A piece of red glass is held in the beam of light from a dispersing prism. How will the spectrum appear?

17. Some blue paints reflect waves that produce the sensation of blue together with a little green. Certain yellow paints also reflect a little green. What becomes of all of the wave lengths of white light that fall upon a mixture of these two paints?

18. What would be the result of mixing paints of all colors together? How does this result compare with that obtained when lights of all colors are mixed?

19. Explain how light can be reënforced and how it can be destroyed by interference.

20. Various colors are visible where oil films are formed on water. How does the origin of these colors compare with those in the spectrum?

CHAPTER XVI

APPLICATIONS OF WAVE THEORY OF LIGHT

201. Explanation of Reflection. — Each point in a candle flame is a source of light waves. These waves travel in all directions with equal speed. Near the source of light the *front of the wave* is a spherical shell (Figure 298), that becomes more nearly plane as the distance from the source increases. The wave-front from a distant source (say 100 feet away) may be considered as a plane. Let such a wave-front ABC (Figure 299) fall upon a reflecting surface. A sends out light in all directions so that its wave-front is the arc R by the time C reaches the mirror. At this time B has reached the mirror and has started a new wave-front S. Then at the instant when C has reached the mirror at C' a line $A'B'C'$ drawn through C' tangent to R and S is the reflected wave, since it is made up of all the reflected elements of ABC. It will be noticed that the whole wave and

FIGURE 298. — Waves of light begin as spreading concentric spheres.

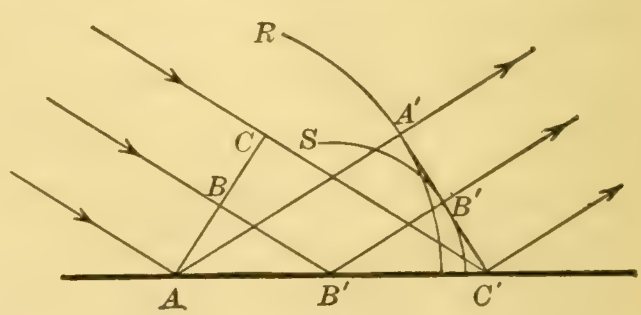


FIGURE 299. — The wave-front ABC becomes $A'B'C'$ by reflection.

each part of it leave the mirror in a direction governed by the law of reflection.

If a plane wave ABC strikes a convex mirror (Figure 300), the center of the wave-front, B, is reflected before A and C reach the mirror. After reflection, the wave-front bulges out as the mirror does, taking the position $A'B'C'$. This wave *appears* to come from I, the location of the *virtual* image of the source of the waves.

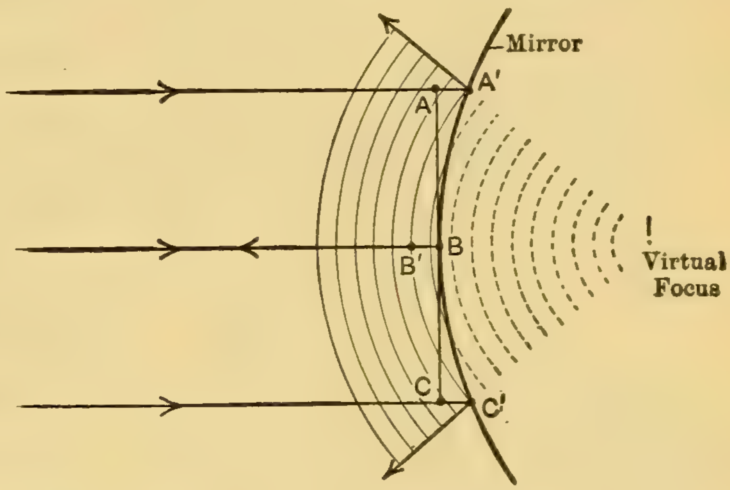


FIGURE 300. — The plane waves ABC becomes the curved wave $A'B'C'$ by reflection from a convex mirror. The new wave *appears* to come from I.

When a plane wave ABC falls upon a concave mirror (Figure 301), the point B is the last to be reflected. A and C have been returned to A' and C' when B reaches the mirror. The reflected wave-front is $A'B'C'$, which actually centers at I, the focus of the mirror forming a real image there, since the waves after centering at this point continue onward with reversed curvature.

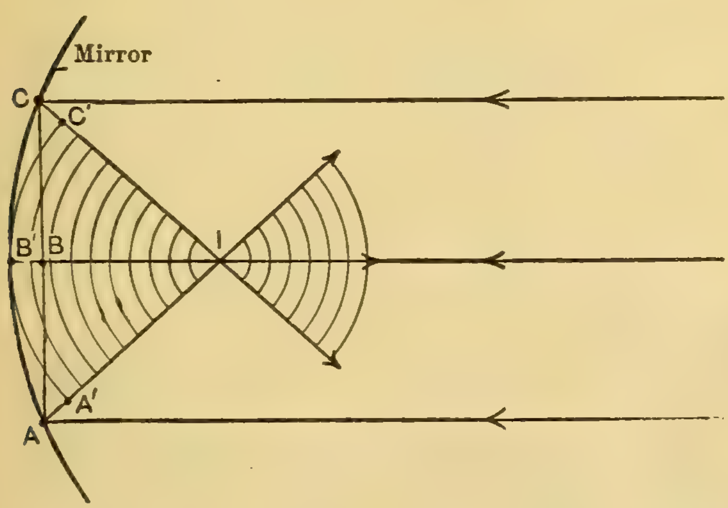


FIGURE 301. — Plane waves from a distant source are reflected so as to focus at I.

If an object O is near a concave mirror (Figure 302), the

wave-front of the light coming from it will not be straight when it strikes the mirror. The front *ABC* becomes *A′B′C′*, which centers at a more distant point, *I*, and forms a real image there.

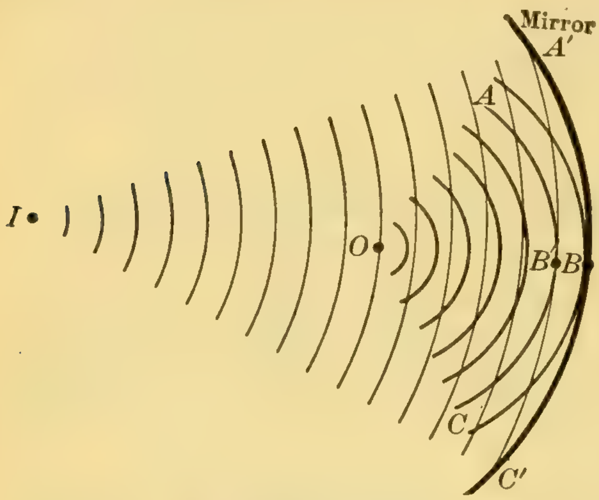


FIGURE 302. — Curved waves from a nearby object, *O*, are reflected so as to focus at *I*.

It can be seen that if the object *O* is very close to the mirror (Figure 303), the curvature of the wave-front is very great, and in reflection it will be reversed, as in *A′B′C′*. This wave appears to center behind the mirror at *I*. The light is really reflected in front of the mirror, but appears to come from the virtual image *I*.

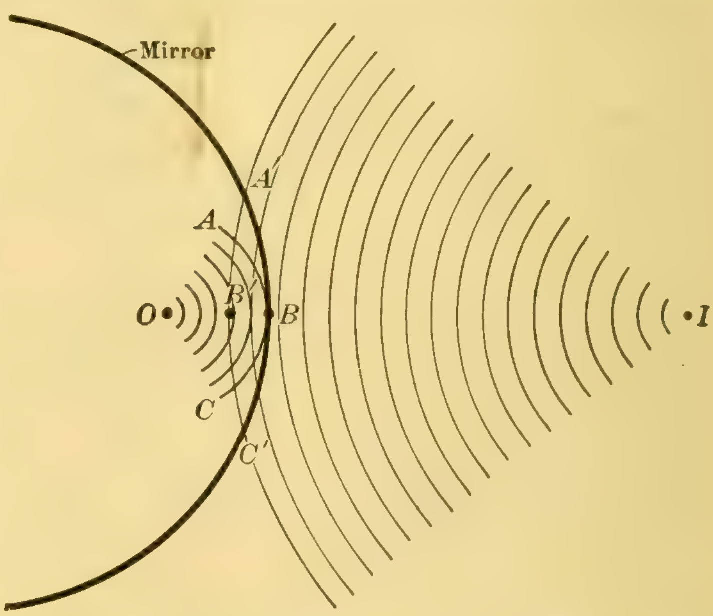


FIGURE 303. — Waves from a source very near the concave mirror are reflected in such a way that the light appears to come from the virtual image, *I*.

202. Explanation of Refraction. — Let the wave *AB* (Figure 304) fall upon the surface, *AB′*, of water. *A*, entering the water first, is retarded and passes through the water only $\frac{3}{4}$ as fast as *B* travels in air. For an instant *B* gains on *A* and the wave-front is turned to *A′B′* as a result. If the wave should emerge from water, the opposite bending would occur.

If the wave-front of light, coming from an object in water, is curved as it reaches the surface (Figure 305, *ABC*), the center of the curve is accelerated while the edges are still in the water. The emerging wave has the front $A'B'C'$, and appears to center at O' which is $\frac{3}{4}$ as deep in the water as the object really is.

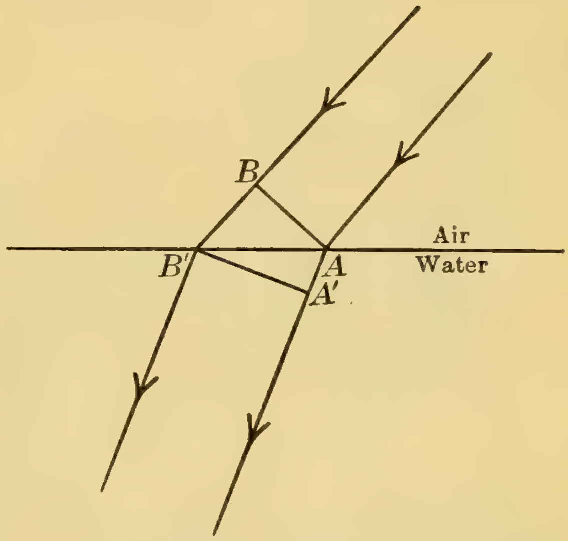


FIGURE 304. — Light travels from B to B' in air while it travels only from A to A' in water.

The refraction of light by lenses under various conditions will be discussed in Chapter XXXI.

203. Index of Refraction. — It has been noted that little progress had been made in finding out the mathematical relations involved in refraction until Snellius formulated the laws of refraction. It was known that different materials refracted light unequally, but the exact relation between the paths taken before and after refraction was not known before this time. This relation may be determined by experiment.

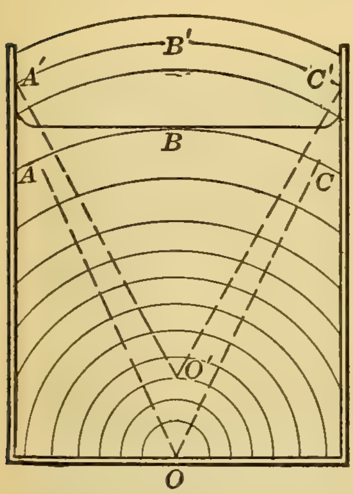


FIGURE 305. — O, below the water, appears to be at O', $\frac{3}{4}$ as deep as it really is.

EXPERIMENT 82. — Place a rectangular piece of plate glass on a sheet of paper and draw a pencil line around the glass so that it may be returned to its original position if moved. Now set a pin against the glass a little above the middle of the side opposite the observer (Figure 306). Looking obliquely through the edge of the glass nearest you, draw a line AB to the edge of the glass in such a manner as to appear to go toward the pin, without being perpendicular to the edge of the glass. Remove the glass and draw BC from B to the pin. Draw the

normal MBN, and with B as a center draw arcs of the same radius across the angle of incidence MBC and across the angle of refraction NBA. From D where the arc intersects BC, drop a perpendicular DF to the normal MB. This line DF is known as the *sine of the angle of incidence.* The corresponding line HK *is the sine of the angle of refraction.* Measure these two sines and divide the value of the sine of the angle of refraction by that of incidence. The quotient thus obtained is the *index of refraction.* If the line AB is drawn at any other angle with the edge of the glass, the sines will be different but the *quotient* resulting from their division will be the same as before, and it will continue constant as long as the same kind of glass is used.

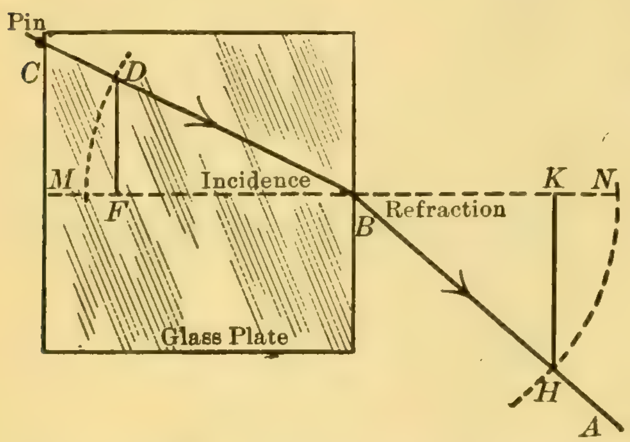


FIGURE 306. — The index of refraction equals HK/DF, the ratio of the speed of light in air to its speed in glass.

The index of refraction is the ratio of the speed of light in air to the speed of light in the given medium. The index of refraction of various substances is given in the table:

Water	1.33	Flint glass	1.67
Alcohol	1.36	Carbon disulphide	1.78
Turpentine	1.47	Ruby	1.8
Crown glass	1.53	Diamond	2.47

The index of refraction of various substances will be referred to in the discussion of total reflection and the aberration of lenses.

204. Total Reflection. — When light falls upon a transparent body obliquely, some of the light is reflected at the surface, while some enters the substance and is refracted. When light leaves a denser medium to enter the air, it is bent away from the normal in accordance with the law of refraction. As the angle of incidence becomes larger, the emergent ray bends closer to the surface of the dense medium.

When the angle of incidence reaches a certain maximum value, called the *critical angle*, the emergent ray coincides with the surface. Now if the ray falls upon the surface so

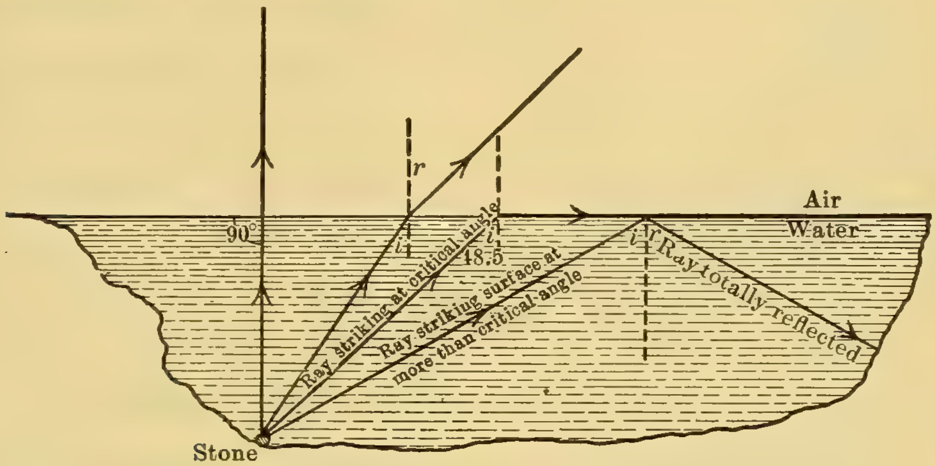
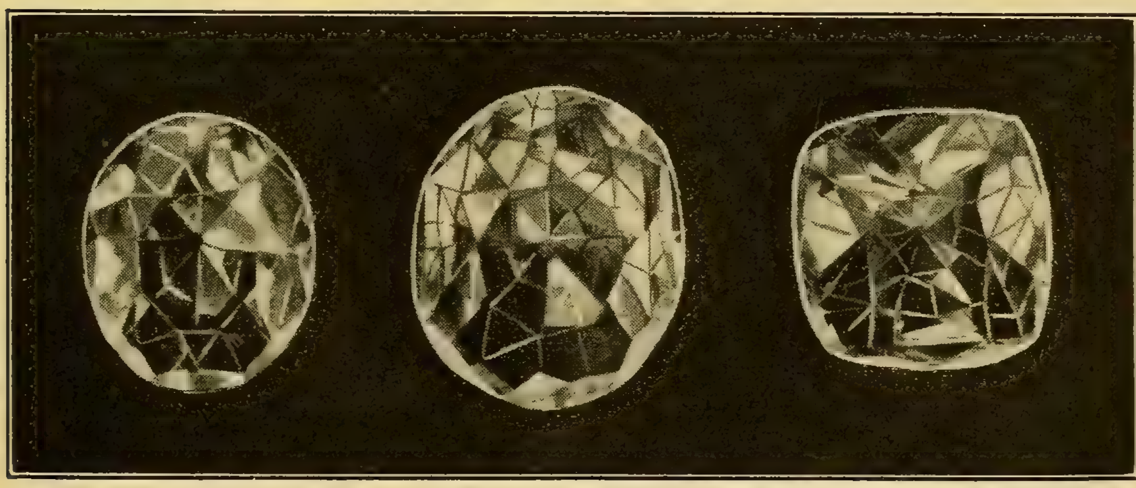


FIGURE 307. — Light passing through a dense medium cannot emerge into a rarer one, if it strikes at an angle greater than the *critical angle.*

that its angle of incidence exceeds the critical angle, the ray cannot emerge from the dense medium into the air, but is reflected regularly back into the dense medium. This reflection is known as *total* reflection (Figure 307). The denser the medium is, optically, the smaller is the value of



Courtesy American Museum of Natural History.

FIGURE 308. — THREE FAMOUS DIAMONDS.

Left, Regent, 136 carats; center, Kohinoor, 125 carats; right, Piggot, 82 carats. Their brilliancy is due to the reflections of the light from many tiny faces before it escapes to the eye.

the critical angle and the more likely total reflection is to occur. Diamonds have a great optical density (index of refraction 2.47), hence rays of light entering the diamond may be internally reflected several times before emerging. The diamond is cut to increase this effect (Figure 308), because of the increased brilliance caused by this total reflection.

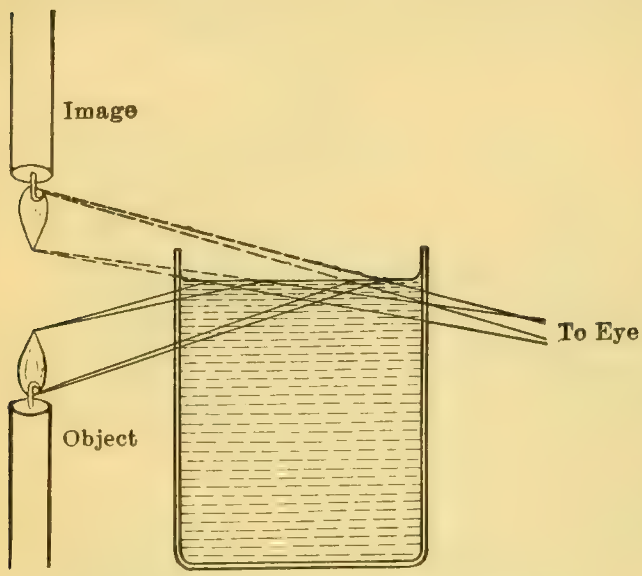


FIGURE 309. — Light, striking the under side of the water-air surface, is totally reflected and an image is formed, as shown.

EXPERIMENT 83.—A simple home experiment will illustrate the total reflection of light by water. Fill a tumbler with water and place it near the edge of a table. Set a lighted candle behind the jar of water. By bending down so that your eye is below the water level, look up against the under surface of the top of the water (Figure 309).

An image of the candle may be seen above the water level, just as though the top of the water were a plane mirror. *What is the path of the rays that form the image? Why do they not pass through the top of the water?*

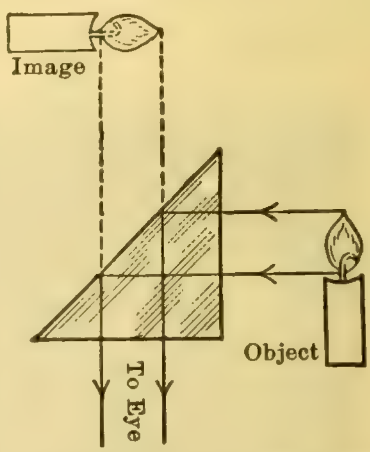


FIGURE 310. — A right triangular prism makes a perfect mirror, because no light is absorbed by the reflecting surface.

The critical angle for crown glass is about 42°, for flint glass about 36°, and for diamond about 23°. If light is allowed to fall perpendicularly upon one side of an isosceles right triangle of glass, it will proceed without refraction to the hypotenuse. The angle which the light makes with the hypotenuse is 45° — a few degrees more than the critical angle. The light is therefore totally reflected

and passes out of the prism at right angles to the other side (Figure 310). This reflection is made useful in the prism field glasses (Figure 311) where by four prisms, the light is made to traverse the length of the cylinder three times. This produces as much magnification as though a tube three times as long were used.

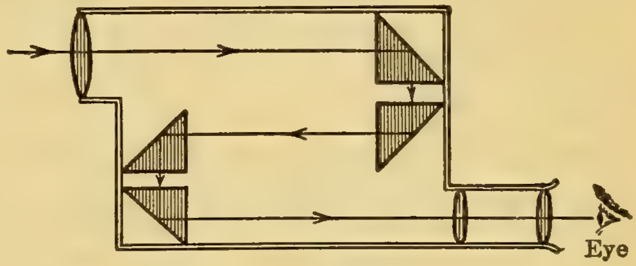


FIGURE 311. — Four triangular prisms reflect the light three times the length of the field glass tube.

A totally reflecting prism is sometimes used instead of a mirror in the eyepiece of reflecting telescopes. One reason for using totally reflecting prisms instead of mirrors is that no light energy is absorbed at the reflecting surface in the case of the prism, while there is a considerable absorption upon the metal surface of the mirror.

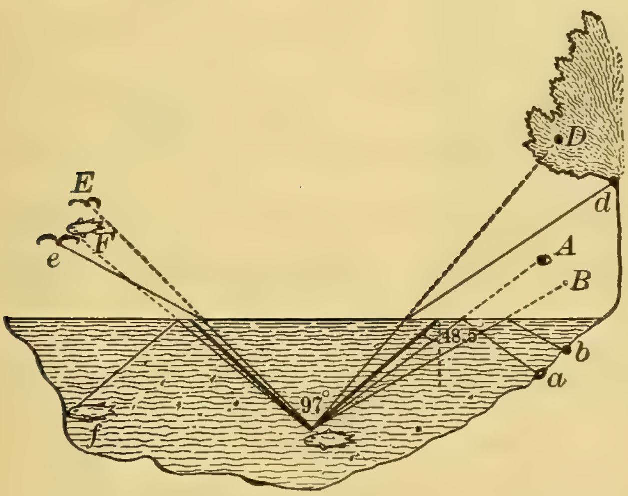


FIGURE 312. — The fish in the center sees a curious mixture of objects under water (reflected) and objects in air (refracted). Small letters are real positions, and capitals, apparent positions.

To the eye of a fish, all objects outside the water appear to lie in a cone whose vertex angle is 97° — twice the critical angle of water (Figure 312). Bordering this conical field of external objects lies the image of the adjacent bottom of the lake or stream in which the fish lives. The small letters in the diagram are to represent the location of actual objects, while the capitals represent the apparent position of the corresponding objects as they appear to a fish.

QUESTIONS

1. What is *refraction?* What causes refraction?
2. What is meant by *index of refraction?*
3. How does the speed of light in water compare with the speed of light in glass?
4. When light enters glass obliquely from air, how is the light refracted? How when light enters glass obliquely from water?
5. How is light refracted when entering glass from carbon disulphide?
6. Why is the word *total* used in describing the reflection of a ray of light trying to enter air obliquely from water?
7. What use is made of total reflection?
8. Define *critical angle.* What is its value for glass? For diamond?
9. Show how a right triangular prism of glass may be used as a reflector. What optical device makes use of this reflection?

205. Different Spectra. — The spectrum is usually associated with the rainbow effect that results from the dispersion of sunlight. This is not the only kind of spectrum that can be made. Any *solid* body, heated to incandescence, emits waves of all lengths and the spectrum of this light is continuous, *i.e.* comprising all colors in an unbroken band from red to violet.

Every element, when converted into a gas and heated to incandescence, emits a light whose spectrum may consist of only a few bands of colored light, scattered throughout the spectrum. The number, color, and location of these bands depend upon the element that is giving off the light. Such a spectrum is called a *bright-line* spectrum. The spectra of several elements are shown on the opposite page.

Careful study of the sun's spectrum discloses the fact that the colored band of light is broken by several hundreds of narrow dark lines (Fraunhofer's lines), forming a *dark-line* spectrum (see illustration). Experiment shows that an

element in gaseous form absorbs the same wave lengths that it is capable of emitting. The interior mass of the sun would form a continuous spectrum, but before its light reaches us, the light must first pass through the sun's atmosphere. The atmosphere absorbs from the light all the wave lengths that the elements of the atmosphere are able to emit. The light from the interior reaches us, therefore, lacking these wave lengths and showing a dark line where each wave has been absorbed.

The dark lines of the sun's spectrum have been identified with the bright lines formed by incandescent elemental vapors on the earth. So we know that some elements that compose the earth's crust must also exist in the sun's atmosphere. One element, helium, was so named because certain dark lines in the solar spectrum could not be assigned to any element then known to exist on the earth. Later, helium was found in certain minerals and afterward in the earth's atmosphere in very small quantities, and recently in natural gas. Spectrum analysis indicates readily the composition of the distant stars or of unknown compounds.

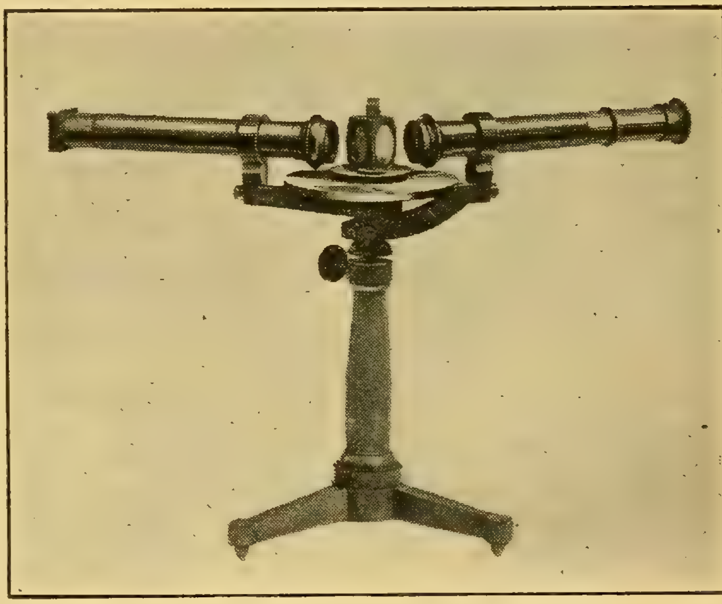


FIGURE 314.—Light falling on the glass prism (center) through a slit in the left tube, is dispersed, and the spectrum studied by the telescope at the right.

Spectra are studied by means of a spectroscope (Figure 314), which consists of a tube directing the light to be ob-

served against a prism, and a combination of lenses for magnifying the spectrum that is formed.

206. Polarization of Light. — Suppose that light is entering your eye from a lamp on the level of the eye. Then the vibrations within the ether will be taking place in an up-and-down direction, in a right-and-left direction, and in all oblique directions between these. Each of these vibrations is still transverse (at right angles) to the forward motion of the light wave to your eye. If you now hold a crystal of tourmaline before your eye, the light passes through the transparent crystal apparently unchanged. A second crystal, parallel to the first, produces no change. But if the second crystal is held at right angles to the first (Figure 315), the two transparent crystals shut off the light completely. Tourmaline, like some other transparent substances, possesses the ability to shut off all the transverse vibrations except those parallel to its long axis. The two crystals, whose long axes are parallel, transmit the same vibration to the eye, but when they are crossed, all vibrations are shut off. This quenching of some waves and transmitting others in one plane only is called *polarization*.

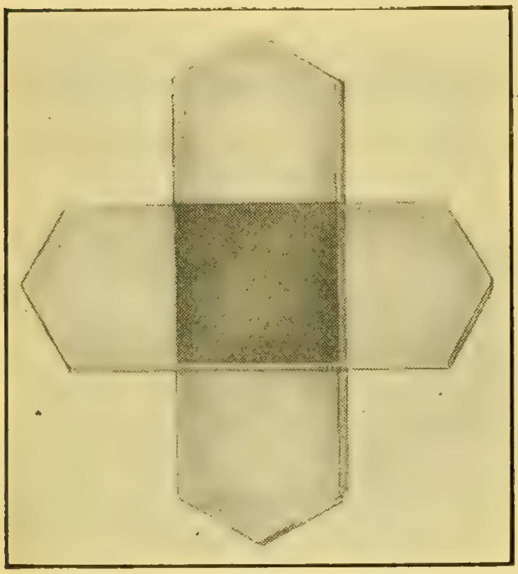


FIGURE 315. — POLARIZATION.

Two tourmaline crystals, each transparent, shut off all light where they cross at right angles.

In Figure 316, the transverse waves of the rope pass easily through two vertical slits, but are checked when they reach the second slit, because this slit is turned so

that it does not permit the waves to pass. Compare this action with that of the tourmaline crystals on light.

The polarization of light is not important because of its effect upon the eye. It is important because most transparent substances can be identified by the effect that they produce upon polarized light.

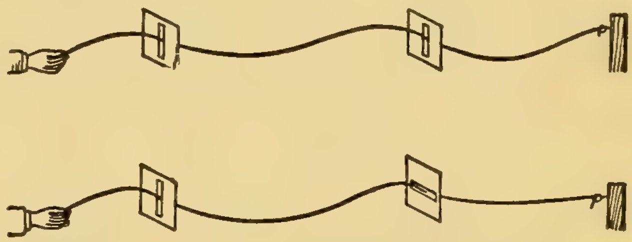


FIGURE 316. — Vertical vibrations pass through vertical slits, but are quenched by the horizontal slit at the lower right.

Most reflecting surfaces polarize light to some extent. The blue of the sky is ascribed to such reflection by very tiny impurities in the air or by oxygen particles. Coarser particles, as dust, smoke, or water droplets, scatter light of longer wave length and cause the brilliant reds and oranges of sunset. The blue and the green of large bodies of water were proved by Tyndall to be due to the fine and coarse silt particles which were contained in the water.

To the student of physics the facts of polarization should constitute a strong proof of the transverse nature of light waves. Sound waves, being longitudinal, cannot be polarized.

QUESTIONS

1. How is a spectrum formed? What is a spectrum?
2. What is a continuous spectrum? How is it formed?
3. What kind of spectrum is formed by an incandescent gas?
4. What is a dark-line spectrum? Give an example.
5. What classes of scientists use spectrum analysis to advance the knowledge of their science?
6. In what ways may light be polarized?
7. How does polarized light differ from light that has not been polarized?
8. If light were a discharge of particles, could it be polarized?

SUMMARY

When light is regularly reflected, each illuminated point of the reflecting surface sends out a new wave, which leaves the reflecting surface in a direction indicated by the law of reflection.

Refraction occurs because the front of a beam of light, falling obliquely upon the surface of a new medium, changes direction, because of a change in the speed of light as it enters the new medium.

The index of refraction is the ratio between the speed of light in air and its speed in a given medium.

Total reflection is the reflection that occurs at the surface of a rare medium when the angle of incidence is so great as to make refraction impossible. **The critical angle** is the maximum angle of incidence at which refraction can occur on entering a rarer medium.

Incandescent solids form **continuous spectra**. Incandescent gases form **bright-line spectra**. Gases absorb the same waves that they emit when incandescent, and therefore light from incandescent solids, after passing through gases, forms **dark-line** or **absorption**, spectra.

Light is polarized when all of the transverse vibrations except those in one plane are shut off by some transparent substance. The polarization of light proves that light waves are transverse.

EXERCISES

1. Explain why a ray of light falling upon a polished surface is reflected so that the angles of incidence and of reflection are equal.

2. Show by diagram the result of a plane wave falling upon a plane mirror; upon a convex mirror.

3. Show by diagram the result of a plane wave falling upon a distant concave mirror; upon a nearby concave mirror.

4. Define the term *index of refraction.* Give examples of the use of the term.

5. By consulting the table of indices of refraction, determine the refraction of a ray of light passing obliquely from glass into carbon bisulphide. Illustrate by diagram.

6. Show by diagram that you understand the total reflection of light. Indicate on your diagram the critical angle.

7. Explain the relation between total reflection and the brilliance of gems. How could perfect reflection be secured by the use of a triangular glass prism?

8. What kind of spectrum is produced by an incandescent gas?

9. Why does sunlight form a dark-line spectrum?

10. What use is made of the analysis of light by dispersion?

11. How can light be polarized? What does polarization of light show about the nature of light waves?

12. A spectrum of an arc lamp is thrown upon a screen. What effect, if any, would be indicated by a radiometer placed just beyond the red end of the spectrum? Can it be shown that there are any ether waves beyond the violet of the spectrum?

13. Under different circumstances, light may be diffused, diverged, or dispersed. Distinguish between the three phenomena and name an object associated with each of them.

14. In a single sentence for each man, give the contribution of each of the following to the science of light: Römer, Newton, Huyghens, Maxwell.

CHAPTER XVII

MAGNETISM

207. Natural Magnets. — The discovery of magnetism is lost in antiquity, for we find in the Greek fables and the Arabian Nights stories of wonderful stones that attracted the iron tip of a shepherd's staff and performed wonders of attraction too great for us to credit. The basis of all this is that in many places deposits of iron ore, now called magnetite, are found which have the property of attracting iron and steel. Not all magnetite has this power of attraction. When it does, such magnetized magnetite is called *lodestone,* which means "leading stone." This name may be due to the fact that the earliest compasses were long pieces of iron magnetized by a lodestone and resting on pieces of wood floating in bowls (Figure 317).

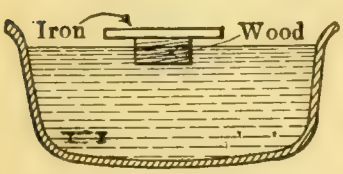


FIGURE 317.—A PRIMITIVE COMPASS.

208. Magnetic Poles are shown by a simple experiment:

EXPERIMENT 84. — Dip a piece of lodestone into a box of small brads. These will be seen to cling in larger bunches at certain points than at others (Figure 318). If the stone is long, these points will be near the ends. The places of greatest magnetic attraction are called *poles.*

Magnetic poles are best seen in artificial magnets, made of hardened steel (Figure 319). These may be bars or may be bent into a U or " horseshoe " shape. If a bar magnet is suspended or pivoted horizontally in a place away from

William Gilbert (1540–1603) was a successful physician who later was appointed physician to Queen Elizabeth. He found time to carry on a wide research into physical and chemical science. His "De Magnete" is still the most important treatise on magnetism. He explained the variation of the compass needle, the action of the dipping needle, and the laws of magnetic attraction. The idea that the earth itself is a magnet originated with Gilbert.

the influence of other magnets, it will turn into a position that is approximately north and south (Figure 320). The pole of the magnet that points to the north is called the *north pole.* The other pole is the *south pole.*

209. Action of Magnetic Poles. — If a bar magnet is suspended, and the north pole of another magnet is brought

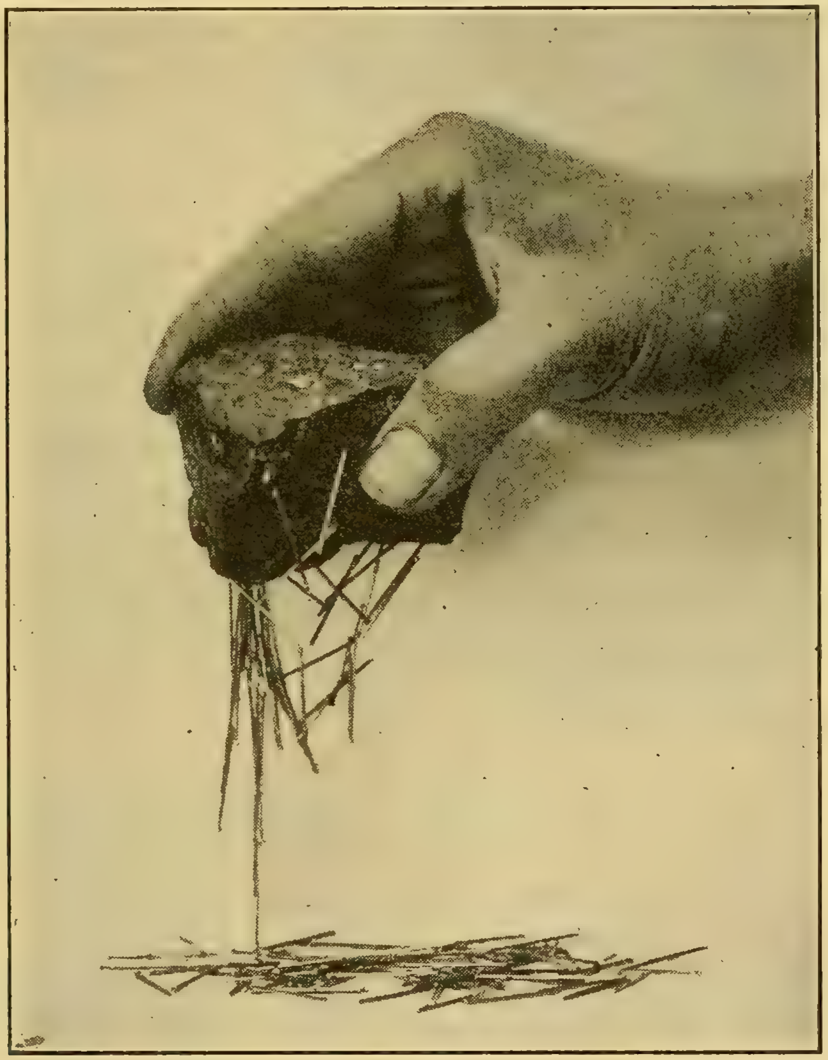


FIGURE 318. — The lodestone shows distinct poles at left and right.

near it, the suspended magnet will swing from its north-and-south position so that its south pole will be attracted by the north pole brought near it (Figure 321). But if the south pole of the magnet in the hand is presented to the south pole of the suspended magnet, they will repel each other.

FIGURE 319. — This bar magnet has been dipped in the pile of small nails, which cling in large numbers at the two poles.

In the same way, the two north poles will repel. These results may be summed up as follows: *Like magnetic poles repel; unlike poles attract.*

The force of attraction or repulsion depends on two conditions, (*a*) the strength of the poles, (*b*) the distance between them. Two good artificial magnets will attract much more strongly than two pieces of lodestone. The fact that permanent magnets have stronger poles than the lodestone can be easily demonstrated by dipping each into iron filings or brads and noting the number attracted.

EXPERIMENT 85. — Dip the pole of a bar magnet into a box of brads. Withdraw the magnet, pick off the brads from the pole and put them in a pile. Place on the brads in the box a piece of cardboard a little larger than the end of the magnet pole. Bring the pole down on the cardboard and again lift out the adhering brads. Place them in a pile beside those first picked up. *Were as many brads attracted as before?*

FIGURE 320. — The magnet, resting on a pivoted saddle, points north and south.

The difference in the action of the poles in the two cases is not due to the interference of the paper with

magnetic attraction, but to the fact that the pole was kept at a little distance from the brads by the cardboard. The force of magnetic attraction and repulsion decreases very rapidly as the distance increases. The attraction between a north and a south pole 2 cm apart is only $\frac{1}{4}$ that at 1 cm; at 3 cm distance the force has decreased to $\frac{1}{9}$. That is, *the force between two magnetic poles is inversely proportional to the square of the distance between them.* Representing the pole strengths by m and m' respectively and the distance between them by d, the force, f, is found from the equation:

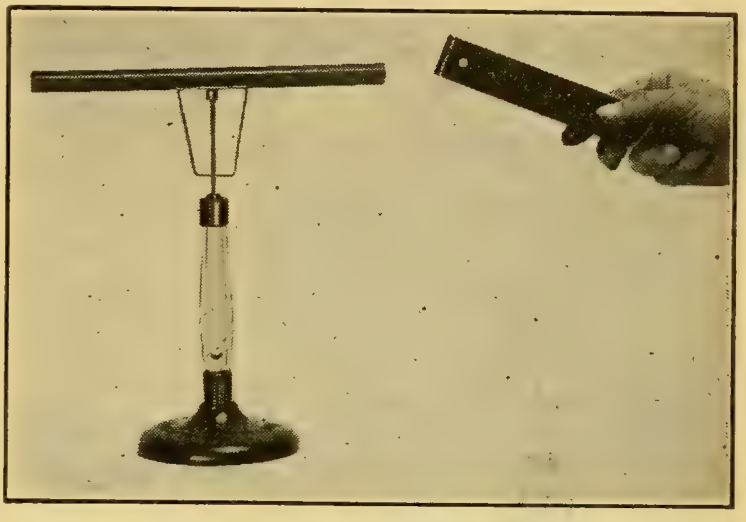


FIGURE 321. — The magnet in the hand attracts the unlike pole of the pivoted magnet and repels the like pole.

$$f = \frac{mm'}{d^2}$$

This relation is of great importance in practical applications of magnetism.

210. Magnetic Substances. — *Magnetic substances* are those which will be attracted by a magnet. Those that are not noticeably attracted are called *non-magnetic*. The most important magnetic substances are the various forms of iron and steel, and practical uses of magnetism are confined to these.

EXPERIMENT 86. — Using a strong horseshoe magnet and a number of substances, including various kinds of iron and steel, nickel, copper,

zinc, any other available metals, wood, glass, hard rubber, sealing wax, etc., find which substances are magnetic and which are not.

211. Magnetic Induction. — We have already seen that one magnetic pole will repel or attract another at some considerable distance. Let us see whether contact between a magnet and an unmagnetized piece of iron is necessary for attraction.

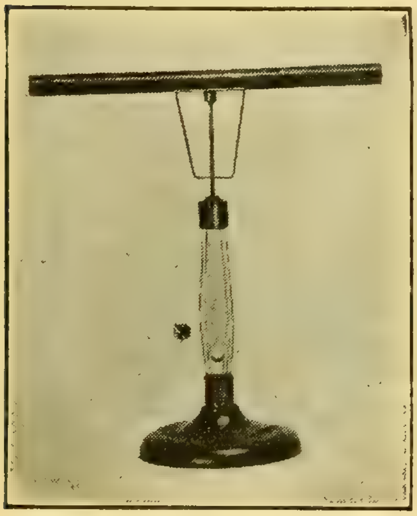


FIGURE 322. — The pivoted bar of unmagnetized iron does not take any special position until a magnet is brought near.

EXPERIMENT 87. — Test both ends of a bar of wrought iron with filings to make sure that it is not a magnet. Support the bar so that it is free to turn (Figure 322). Bring the north pole of a magnet near one end of the bar. *Result?* Bring the north pole near the other end. *Result?* In the same way, test both ends with the south pole. *Results?* Remove the bar from the swing and replace it with the magnet. Bring the bar near the north and the south pole of the magnet successively. *Results?*

The foregoing experiment shows that magnetic attraction does take place at a distance. It also shows that either pole of a magnet will attract an unmagnetized piece of iron, and that the iron will attract either pole of the magnet. That is, the force is not the attraction of the magnet *for* the iron, but the attraction *between* the magnet and the iron. By *magnetic induction,* a piece of iron near a magnetic pole acts like a magnet. The adjacent ends of iron and magnet have opposite polarity, while the farther end of the iron has a pole like the inducing pole. This is shown in the following experiment.

EXPERIMENT 88. — Select a number of nails of different sizes. Pick up the largest with a strong bar magnet. To the lower end of this

nail present a smaller nail, and repeat this with nails of diminishing size until no more will cling (Figure 323). Bring a magnetic needle near the lower end of the last nail. *Is the polarity of this nail the same as that of the magnet, or is it different? Why does the first nail stick to the magnet? Why does each cling to the one above?*

Carefully detach the first nail from the magnet. The nails will now fall apart, because the poles produced in each case were due to the inductive effect of the preceding nail.

Magnetic induction is the production of poles in a magnetic substance by placing the substance in a field of magnetic force.

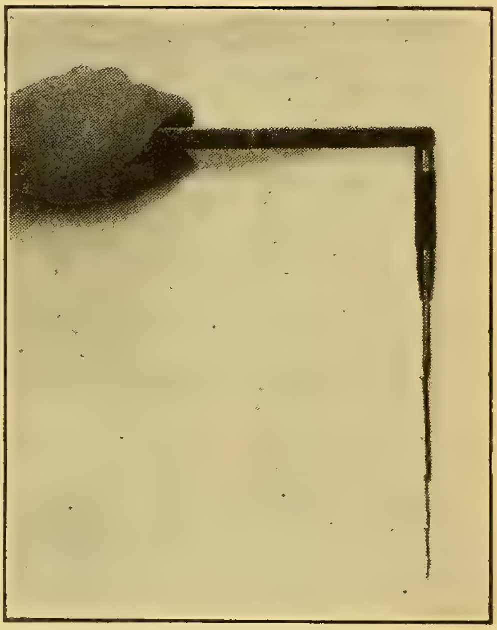


FIGURE 323.—The screw driver and nails are magnetized by induction.

212. Temporary and Permanent Magnetism.—The nails lost their magnetism almost entirely when they were removed from the magnet. Their magnetism was *temporary*. The magnet has retained the greater part of the magnetism given to it when it was made. Such magnetism is *permanent*. Permanent magnets are usually made of hardened steel. Most magnetic substances show temporary magnetism only; pure wrought iron and soft steel are especially suited for making temporary magnets.

213. Theory of Magnetism. — The facts of magnetism are most easily accounted for by assuming two things: First, every molecule of a magnetic substance is itself a magnet; second, in an unmagnetized substance these molecular magnets are pointing in many directions, on account of the mutual attraction between their poles (Figure 324). When the north pole of a magnet is brought near a piece of iron, the molecules swing around so that their south poles are

pointing toward the north pole of the magnet. Magnetizing a body, then, consists in turning the molecular magnets so that their poles point in the same direction (Figure 325).

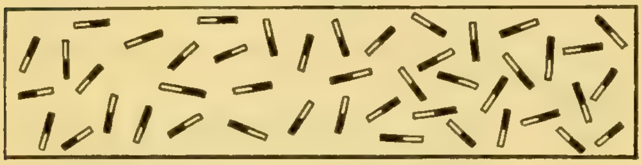


FIGURE 324. — UNMAGNETIZED IRON.

The molecules are represented as rods simply to make the location of their poles more evident.

At one end of a magnet, north molecular poles will make the outside layer, and this will be a north pole; at the other end, there will be a south pole for a corresponding reason. Throughout the body of the magnet, the attraction for each other between these unlike molecular poles keeps the magnetism from being noticed.

This theory of magnetism is supported by many other facts. Heating or jarring a magnet weakens it greatly; both of these processes make it easier for the molecules to move. A magnet rapidly magnetized and demagnetized becomes heated, thus indicating molecular motion. A transformer core is magnetized by a current that changes direction 120 times a second. The molecules of iron in the core must change ends just as frequently, and they thus give rise to a low-pitched hum. Careful measurements have shown a slight increase in length when a bar is magnetized. Striking support is found for the theory of molecular magnets in the fact that if a magnet is broken in the middle, opposite poles are found on either side of the break.

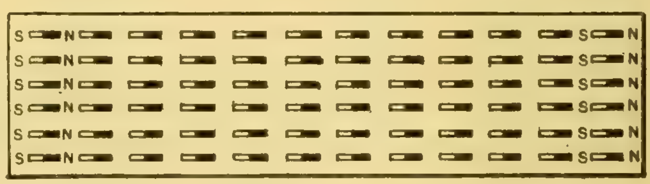


FIGURE 325. — MAGNETIZED IRON.

The molecules have lined up. At one end of the bar, the molecules unite to form the *N* pole and at the other end, the *S* pole.

The difference between permanent and temporary magnets, according to this theory is due to the ease with which the molecules return to their haphazard arrangement when the magnetizing force is removed. It is notable that permanent magnets are made of hard materials, in which cohesion is greater than in the soft iron and steel that form temporary magnets. It would appear that there is greater friction between the molecules in permanent magnets than in temporary magnets.

214. Methods of Making Magnets. — All magnets are made by induction. Two different methods of induction are illustrated in the following experiments.

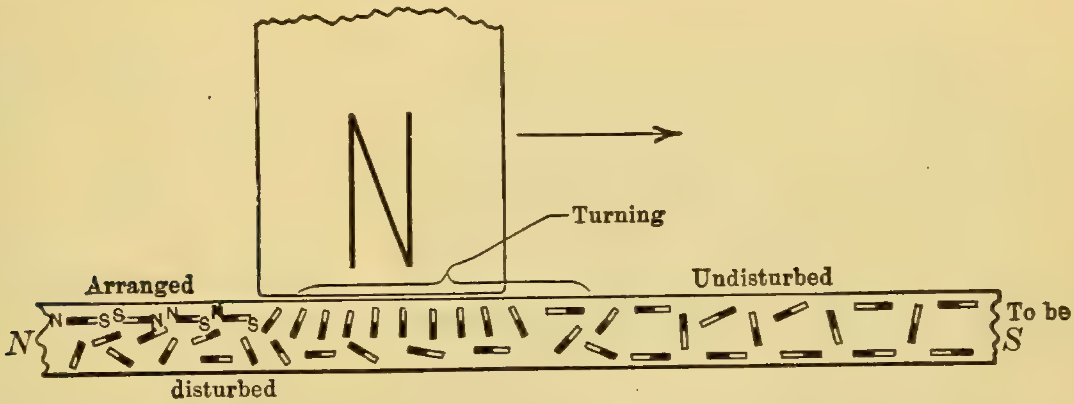


FIGURE 326. — The molecules are swung around into position by the N pole as it passes.

EXPERIMENT 89. — With one pole of a strong permanent magnet rub a knitting needle from end to end, returning to the end first rubbed over a path like one of the lines of force shown in Figure 335. This should be repeated a number of times. Test the needle for poles by dipping into iron filings, and by bringing each end in turn near a compass needle. *Results?*

Rubbing the N pole of a magnet along the needle brings the magnetizing force so close to the molecules in the needle that these molecules turn their S poles in one direction to face the moving N pole of the magnet (Figure 326). Thus these molecules are left so that the end of the needle last

touched by the magnet pole will be a pole opposite in sign to the magnetizing pole. This method, while simple, does not make very strong magnets.

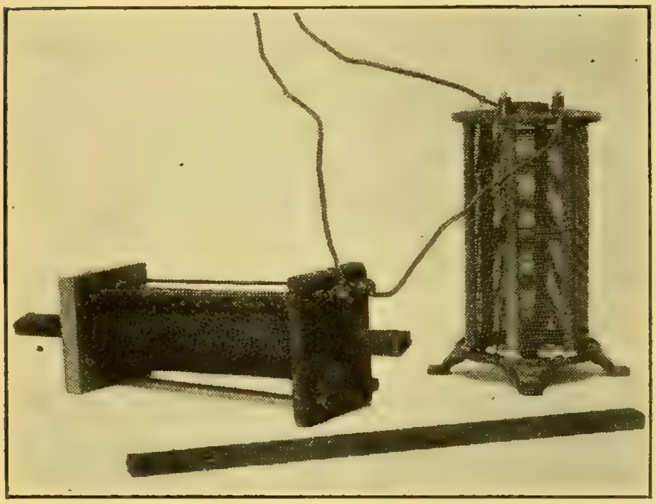


Figure 327. — Current through wires at the top is regulated by the resistance at the right. One steel bar is in position in the coil, and another is waiting to be magnetized.

The best way of making a magnet is to use an electric current. The steel to be magnetized is placed within a coil of insulated wire and an electric current is passed through the coil (Figure 327). Tapping the steel while the current is passing aids the molecules to rearrange themselves and results in a stronger magnet. This is the method used in making magnets commercially. The induction of magnetism by the electric current will be more fully explained in Chapter XVIII.

Figure 328. — A Magnetic Needle. The paper flag is attached to enable the class to identify the *N* pole.

Long, thin artificial magnets, so made that they may be readily balanced on a pivot, are called *magnetic needles* (Figure 328). They are used in magnetic compasses, and are of great value in the experimental study of magnetism.

QUESTIONS

1. Describe natural magnets as to (*a*) origin; (*b*) strength; (*c*) action on magnetic substances.

2. Where are the poles of a magnet located? Describe fully the action of the poles of two magnets on each other.

3. Upon what two quantities does the force between two magnets depend?

4. What is the difference between the material used in permanent and in temporary magnets?

5. Describe in detail what takes place in a piece of iron when it is brought near a magnet. What is this action called?

6. Describe two methods of making a permanent magnet. Which makes the stronger magnet?

7. What is a magnetic needle? For what are magnetic needles used?

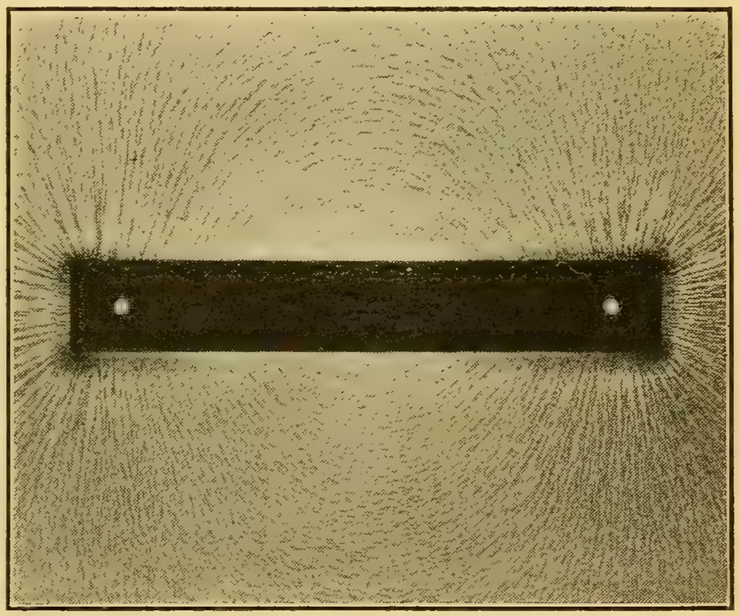


FIGURE 329.—LINES OF FORCE AROUND A BAR MAGNET.

The iron filings become magnets by induction and arrange themselves along lines of force.

215. Magnetic Lines of Force. — We have already seen that the attractive force of a magnet makes itself felt most strongly in the vicinity of the poles. Magnetic effects are noticeable, however, for a considerable distance in the space surrounding the magnet. This space is called the *magnetic field,* and it is convenient to speak of the direction in which magnetic force is acting at any point as a *magnetic line of force.* Simple experiments give us much information regarding the lines of force.

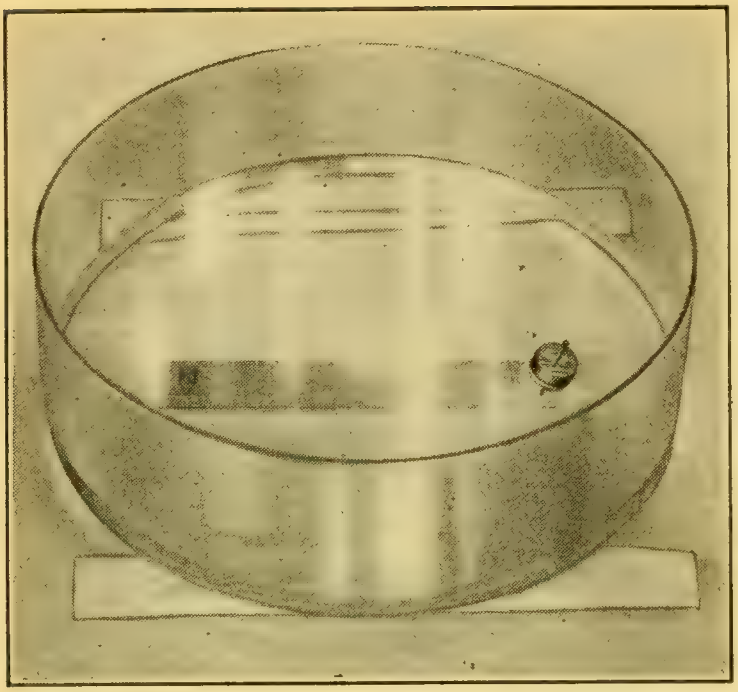


FIGURE 330. — Wherever it is placed, the N pole at the bottom of the floating magnet will move along lines of force.

EXPERIMENT 90. — Support a sheet of cardboard or glass over a bar magnet by strips of wood of the same thickness as the magnet. From a height of about 2 feet sift fine, dry iron filings on the cardboard. Tap the cardboard lightly with a pencil to permit the filings to arrange themselves under the induction of the magnet. The curved lines of filings mark the location of some of the lines of force of the magnet (Figure 329). *Why do the filings arrange themselves in lines?* (See Experiment 88.)

EXPERIMENT 91. — Using wood strips of the same thickness as the magnet, support a large flat-bottomed glass dish over a bar magnet. Put about half an inch of water in the dish. Magnetize a steel pin so that the head is a N pole, pass it through a thin slice of cork, so that when the cork is floated on the water in the dish, the head of the pin will just clear the bottom (Figure 330). Place the pin with its head just above the corner of the N pole of the magnet that is below the dish. Watch the movement of the floating needle. It will follow a line of force, because of the repulsion of the adjacent N poles. The point of the pin is so much farther from the pin than the head that its magnetic effect is very little. By starting at other points

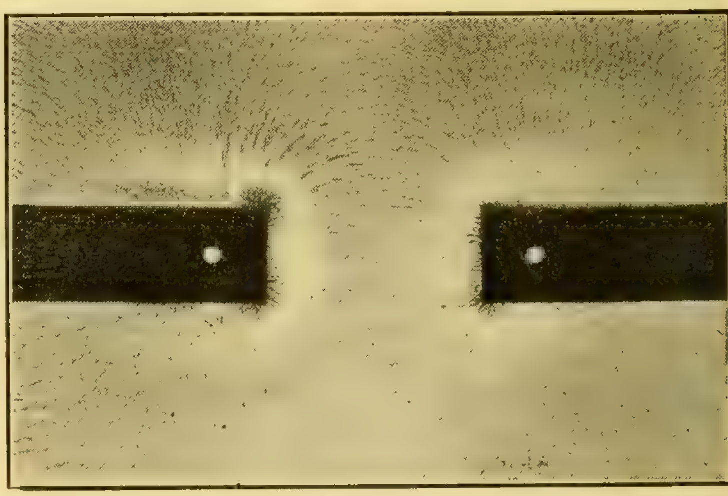


FIGURE 331. — LINES OF FORCE BETWEEN UNLIKE POLES.

If they were elastic bands, they would draw the poles together.

on the N pole, other lines of force may be located.[1] This experiment illustrates a useful definition of a line of force; *the path taken by a free north pole.*

Experiment 92. — Between the strips used in Experiment 90 place two magnets, with opposite poles facing each other and about 2 inches apart (Figure 331). Cover the magnets with cardboard and sprinkle iron filings on the cardboard, as before. Tap the cardboard lightly. Carefully examine the strings of filings that outline the lines of force. *Do they cross each other?*

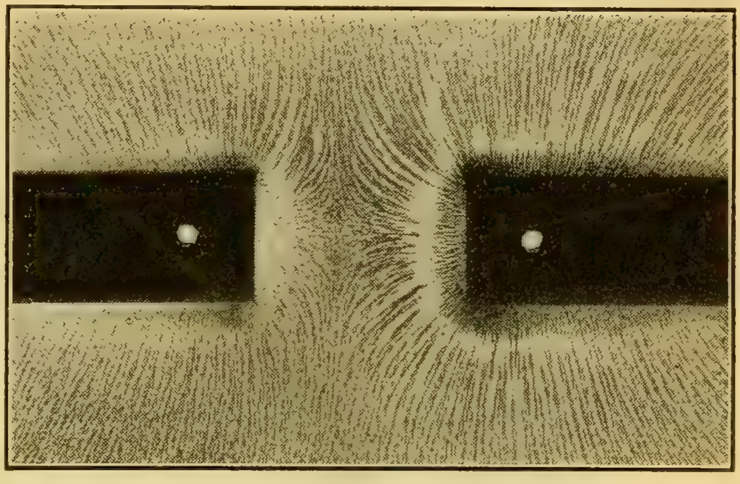


Figure 332. — Lines of Force between Like Poles.

Notice their repulsion and the space in the center free from lines.

Reverse one of the magnets, so that like poles face each other, and again locate the lines of force with the iron filings (Figure 332). Notice particularly the position of the lines near the poles, remembering the experimental fact that like poles repel.

The magnetic figures obtained in the experiments just described are of great service in showing the conditions in a magnetic field. The line of force passing through any point shows the direction of the magnetic force at that point (Figure 333). The crowding of the lines near the poles and their greater separation at more distant points serve to picture the change in the strength of the magnetic field as we get farther from the poles. The strength of the field at different points

[1] In demonstrating this experiment to a class, either place the apparatus on the horizontal condenser of a lantern arranged for vertical projection, or place behind the dish on the table a large mirror inclined at the proper angle toward the class. In the latter case a little paper flag should be mounted on the point of the pin.

is expressed in terms of lines of force per square centimeter at the point considered. Faraday, who conceived the picturing of the magnetic field in terms of lines of force, endowed these imaginary lines with certain properties that are of great service in expressing the facts of magnetism and electromagnetism. He represented them as being like stretched elastic bands, which would therefore tend to shorten lengthwise, and which repelled each other sidewise at the same time. An examination of the magnetic figures produced by the action of unlike poles on iron filings shows the foundation for both of these ideas. These poles *do* attract, as if pulled by elastic bands, and the lines *do* bulge away from each other, as if repelling. The curves obtained with *like* poles picture the repulsion that actually takes place.

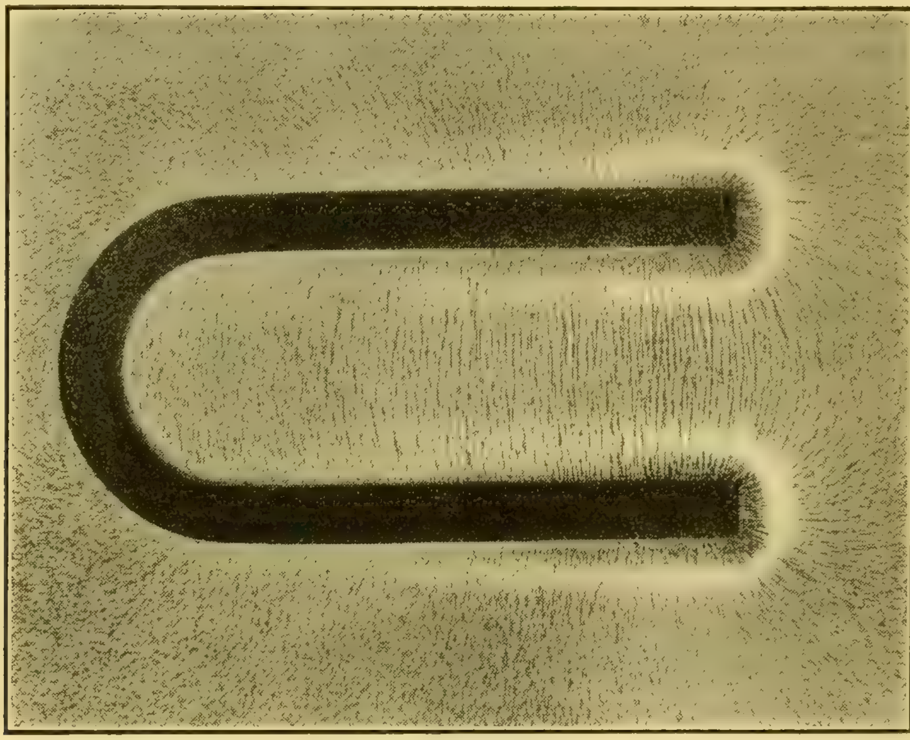


FIGURE 333. — LINES OF FORCE OF A HORSESHOE MAGNET.

By bending the steel into this form, the distance between the poles is shortened and the field between them made very strong.

A compass needle, placed in a magnetic field, sets itself

tangent to the lines of force (Figure 334). For the description of some electrical facts, it is convenient to assign direction as well as position to lines of force. *By agreement among physicists,* lines of force are said to come out of the N pole of a magnet and enter the S pole (Figure 335). They then continue through the magnet to the N pole, *forming closed curves.* The molecular magnets within the steel or iron arrange themselves along lines of force, just as the compass needles do outside the magnet. A N pole therefore is any place from which magnetic lines pass out into the magnetic field, and a S pole as the place where they enter the magnet.

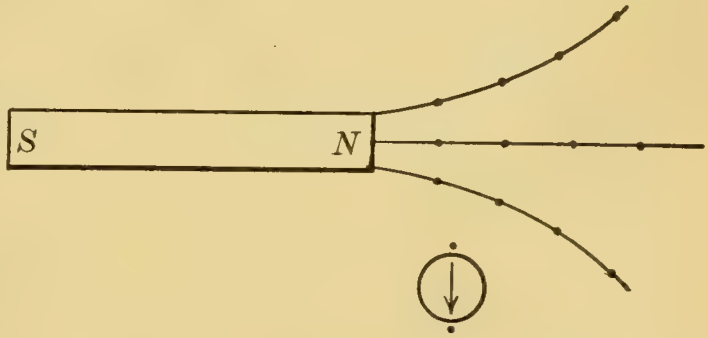


FIGURE 334. — TRACING LINES OF FORCE WITH A COMPASS.

Starting at a point on the magnet, a dot is placed at the N pole of the compass, which is then moved forward until the S pole is on this dot, and the process continued.

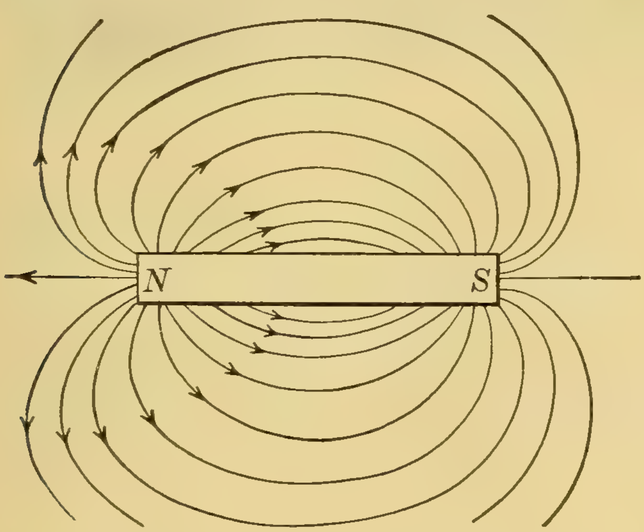


FIGURE 335. — The lines of force come out of the N pole and enter the S pole. Their path through the magnet back to the N pole is not shown. Students' drawings of magnetic fields should show a few lines, with direction arrows, as in this figure.

216. Properties of Magnetic Lines of Force. — The properties described in the last section may be summarized as follows:

(1) Lines of force show the direction of force in a magnetic field. They represent the paths of a free N pole.

(2) They are closed curves, coming out of the N pole of a magnet and entering it at the S pole, returning through the magnet.

(3) They never cross each other, tend to shorten lengthwise, and repel each other sidewise.

(4) Their concentration is a measure of the strength of the magnetic field.

EXPERIMENT 93. — Place the two bar magnets with their opposite poles facing each other, but at a greater distance than in the last ex-

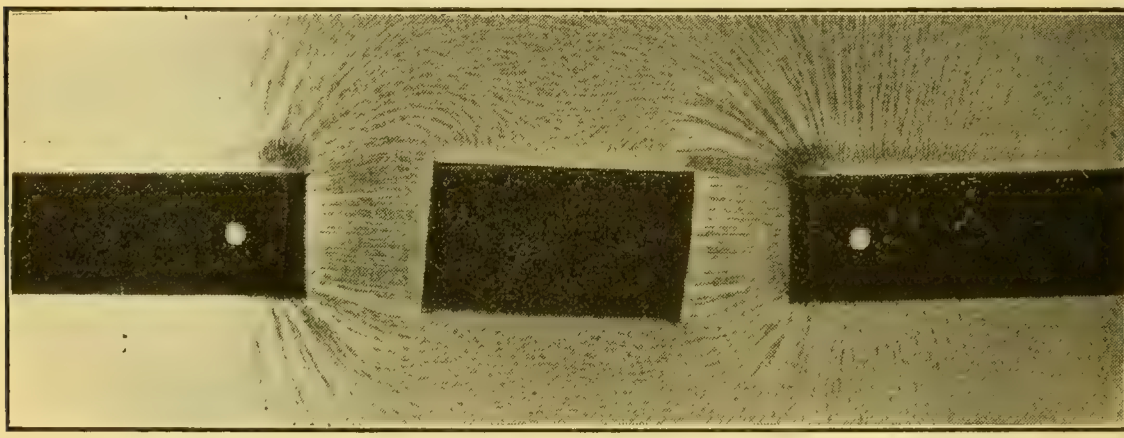


FIGURE 336. — Lines of force turn from the air into the iron, because the iron has greater permeability than air.

periment. Midway between the poles lay a disk or a rectangular piece of soft iron (Figure 336) of the same thickness as the magnets. Locate the lines of force with the iron filings, as before. *Do the lines tend to crowd toward the iron or to be spread away from it? Does the iron act as if it had poles? If so, are the poles of the iron like or unlike the adjacent poles of the magnet? Do lines of force pass more easily through air or through iron?*

217. Permeability. — The whole number of lines in a particular field of force is called the *magnetic flux.* The entire flux of any particular magnet passes through the magnet itself from the S pole to the N pole. It is therefore seen that the concentration of the lines is much greater in the iron than in the air. This concentration is the measure

of the strength of the field. The effect of the iron placed between the unlike poles in Experiment 93 showed the same thing. The greater concentration of the lines of force in iron than in air is briefly described by saying that iron has greater *permeability* (" go-through-able-ness ") than air.

Whenever a piece of iron is placed in a magnetic field, the lines of force are bent out of their previous course in such a way as to show that " iron is a better carrier of lines of force than air." Non-magnetic substances, such as wood, paper, copper, and aluminum, do not deflect the lines of force. The cardboard screens and the glass dish and water used in our experiments do not in any way affect the direction or number of the lines of force from the magnets. We express this fact by saying that the permeability of such substances is 1. The same magnetizing force that will set up one line of force per square centimeter in air may set up 1000 or 1500 lines per square centimeter in different kinds of iron.

Magnetic induction in iron may be considered as due to its great permeability. The lines from the field crowd into the iron and turn the molecules as already has been described. The use of iron cores in electromagnets, explained in the next chapter, is due to the great permeability of the cores, causing them to concentrate practically all the lines of force produced into a relatively small space. In order to preserve permanent magnets from loss of strength, their poles are usually connected by pieces of soft iron. The great permeability of the iron " keeper " furnishes a short, closed path for the lines of force of the magnet, and thus retains the molecules of the magnet in their regular arrangement.

There is no insulator for magnetic lines of force. If, therefore, we wish to protect a watch or an electrical measuring instrument from external magnetic fields, we surround it as

far as practicable with soft iron. The lines of the field crowd into the surrounding iron case, thus leaving the space within nearly free from magnetism. Such a protecting case is called a *magnetic screen.*

While the actual permeability depends on the strength of the magnetizing force, for a given magnetizing force cast iron is least permeable of the magnetic materials. Of greater permeability in the order named are cast steel, wrought iron, and special sheet steel used in making armature and transformer cores. The opposite of permeability, that is, the opposition to the passage of lines or force, is called *reluctance.* In a magnetic circuit, we make the air gaps as small as possible, because of the great reluctance of air.

218. The Earth as a Magnet. — The behavior of the compass needle indicates that the earth itself is a great magnet. Compass needles show the direction of the lines of magnetic force of the earth. The presence of such lines of force can also be shown by their inductive effect.

Experiment 94. — Select a bar of wrought iron that is entirely unmagnetized, as shown by its attracting either pole of a magnetic needle when the bar is held in a horizontal position. Place the bar in a north-and-south line and turn it so that it will make an angle of from 60° to 70° with the horizon (Figure 337). While the bar is held in this position, bring the magnetic needle near the upper end and the lower end in turn. *Are poles now present at the ends? At which end is the N pole? What does this indicate regarding the direction of the earth's lines of force?*

With the bar still held in an inclined position, hammer one end sharply several times. Now test it for permanent poles. *Describe their location.* Again place the bar in the inclined position, but with the ends reversed, and hammer it a second time. *Have the poles been reversed by this process?*

While the magnetic field of the earth is weak compared with that near a permanent magnet, these experiments show

that it does exist. Steel umbrella rods, vertical steel pipes, girders, and machine tools are usually found to be permanent magnets, as the result of the inductive effect of the earth's magnetism. Their *N* poles are always at the bottom. We may then conclude that the earth is a spherical

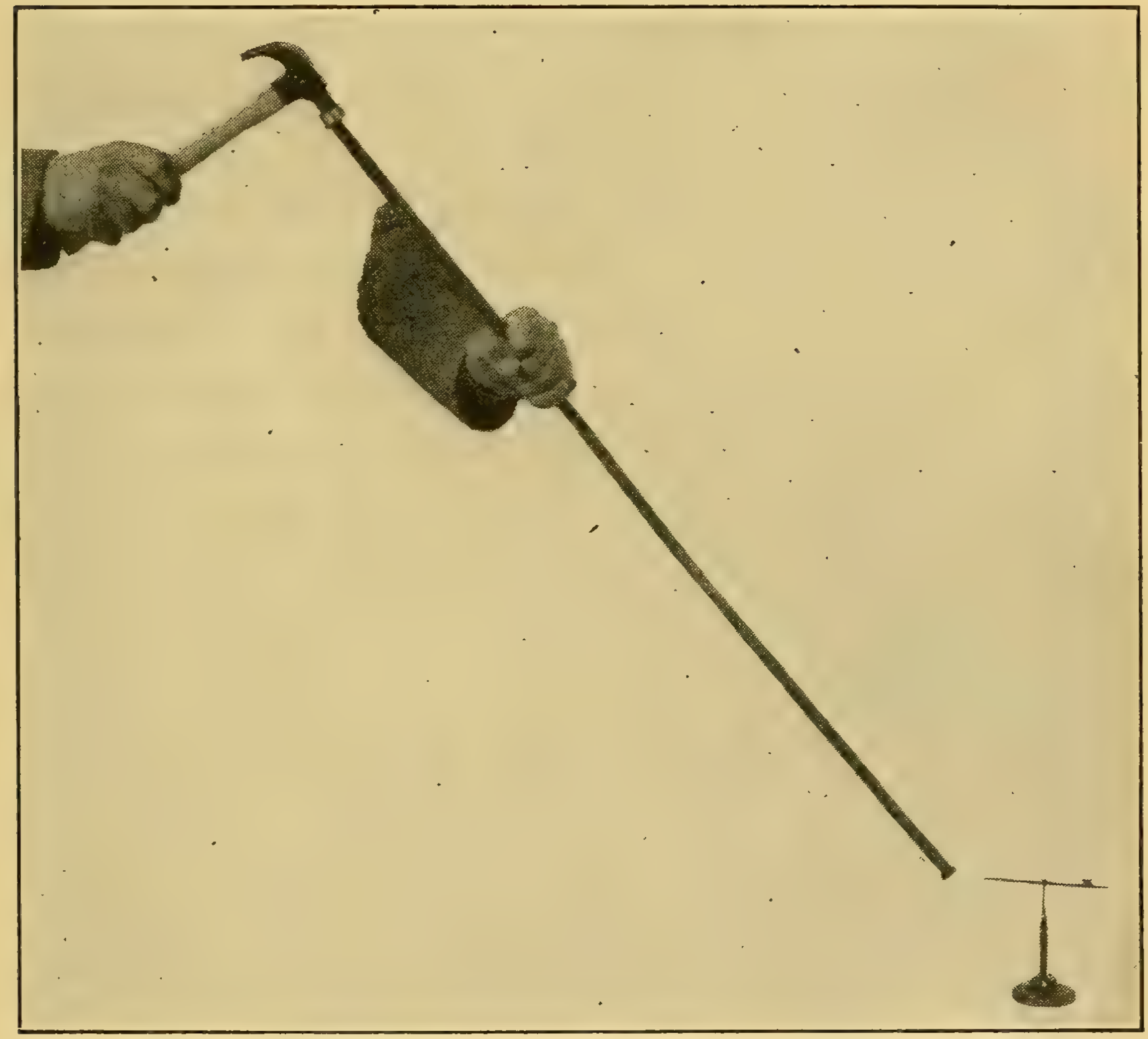


FIGURE 337. — Placing the iron bar in the direction of the earth's field allows the greatest number of lines to pass through it, and hammering the lines helps the molecules to turn.

magnet with two poles, one in the northern and one in the southern hemisphere. According to the naming we have adopted for compass poles, the earth's pole in the northern hemisphere must be a *S* pole, and that in the southern hemisphere a *N* pole.

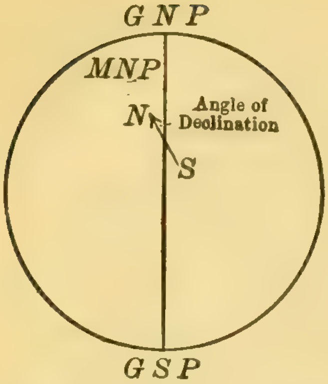


FIGURE 338. — DECLINATION.

The geographic poles are marked *G* and the magnetic pole *M*.

219. Declination. — If a compass is observed outdoors on a starry night, it will be found that in most places it will not point directly at the North Star, but may point more than 20° west of it in Maine and 20° east of north in Oregon. This shows that the magnetic lines of force of the earth do not in general coincide with the north and south meridians of longitude. The angle between the direction of the needle and the meridian at any place (Figure 338) is called the *variation* or *declination* at that place. Very careful determinations of declination are constantly being made by the various governments of the world and recorded on maps and charts for the use of surveyors and navigators, since without this information compass directions would be very misleading.

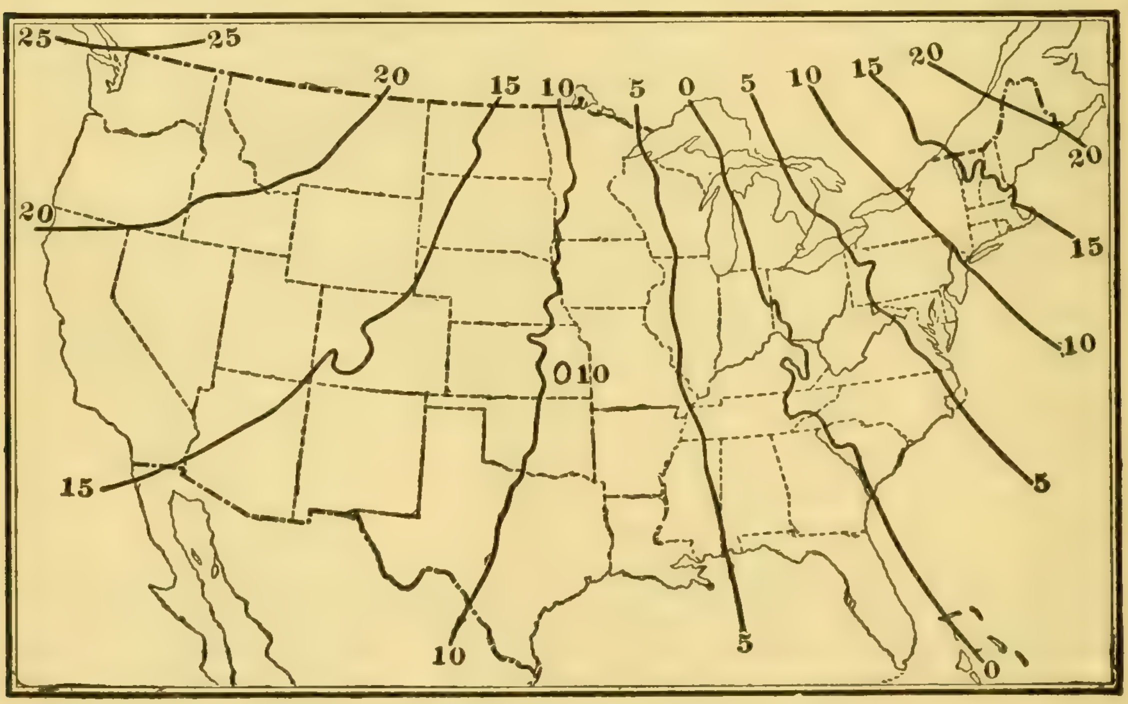


FIGURE 339. — ISOGONIC LINES IN 1920.

The agonic line is marked *O-O*. Note the great difference in the declination in different parts of New York State.

Figure 339 shows lines that connect places of equal declination for the western hemisphere. These lines are called *isogonic* lines, and the line of no declination is called the *agonic* line. Columbus discovered the failure of the needle to point north at all places on his trip across the Atlantic. The agonic line at that time was called the *Columbian line,* and lay much nearer Europe than at present. It will be noted that the isogonic lines do not converge toward the north geographical pole, but toward a point north of Hudson Bay.

220. Dip. — If a steel needle is carefully balanced horizontally on its pivot and magnetized, the *N* pole will then incline downward somewhat in the northern hemisphere and the *S* pole in the southern hemisphere. When a balanced needle is so supported that it can turn in a vertical plane (Figure 340), after magnetization it will *dip,* often to a considerable extent. To measure this dip, a vertical circle is mounted beside the needle, and the dipping needle is turned until the plane of the needle is in a magnetic meridian. The angle between the needle and the horizontal is called the *angle of inclination* or *angle of dip.* This increases as we go north and decreases as we go south, until the needle becomes horizontal at certain points near the earth's equator. These points lie on the magnetic equator. South of the magnetic equator, the *S* pole dips. Lines of equal dip are called *isoclinic lines,* and are shown in Figure 341. The dip in the United States varies between 55° and 78°.

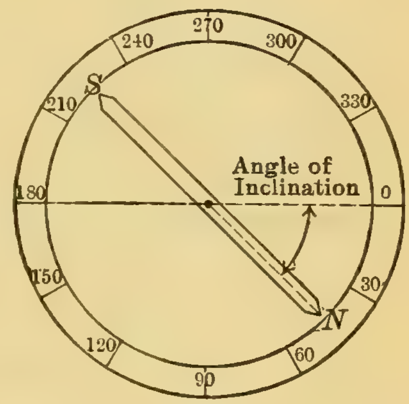


FIGURE 340. — A DIPPING NEEDLE.

It would have about this inclination in Cuba.

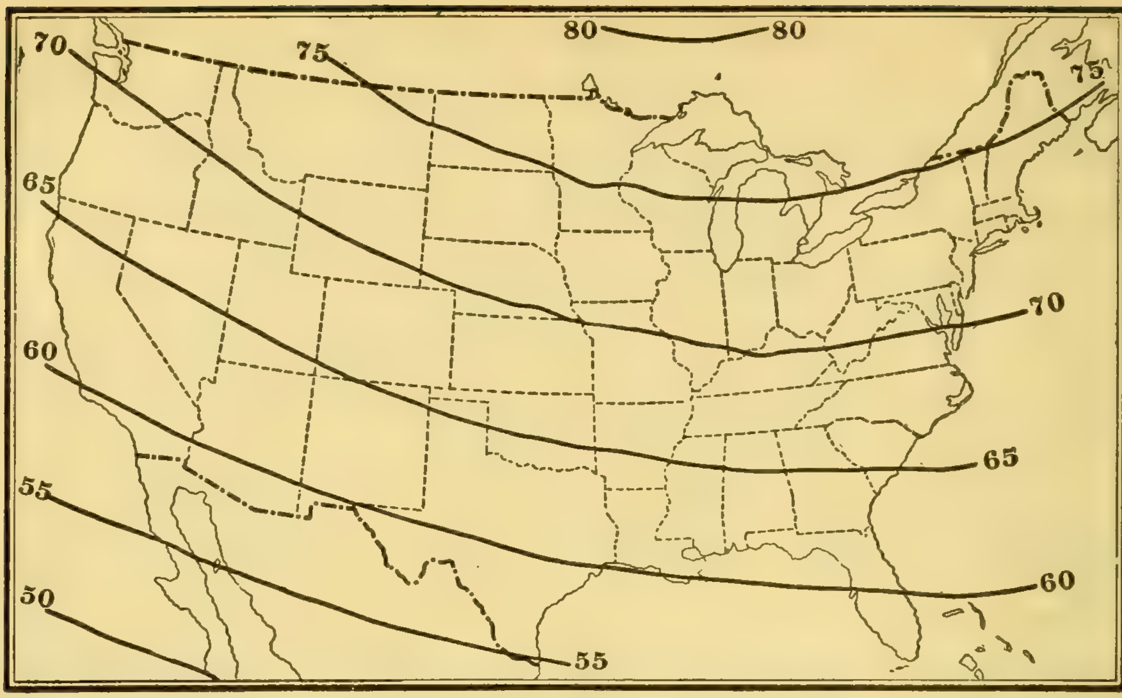


FIGURE 341. — ISOCLINIC LINES IN 1915.

The inclination and declination at a given place change from year to year.

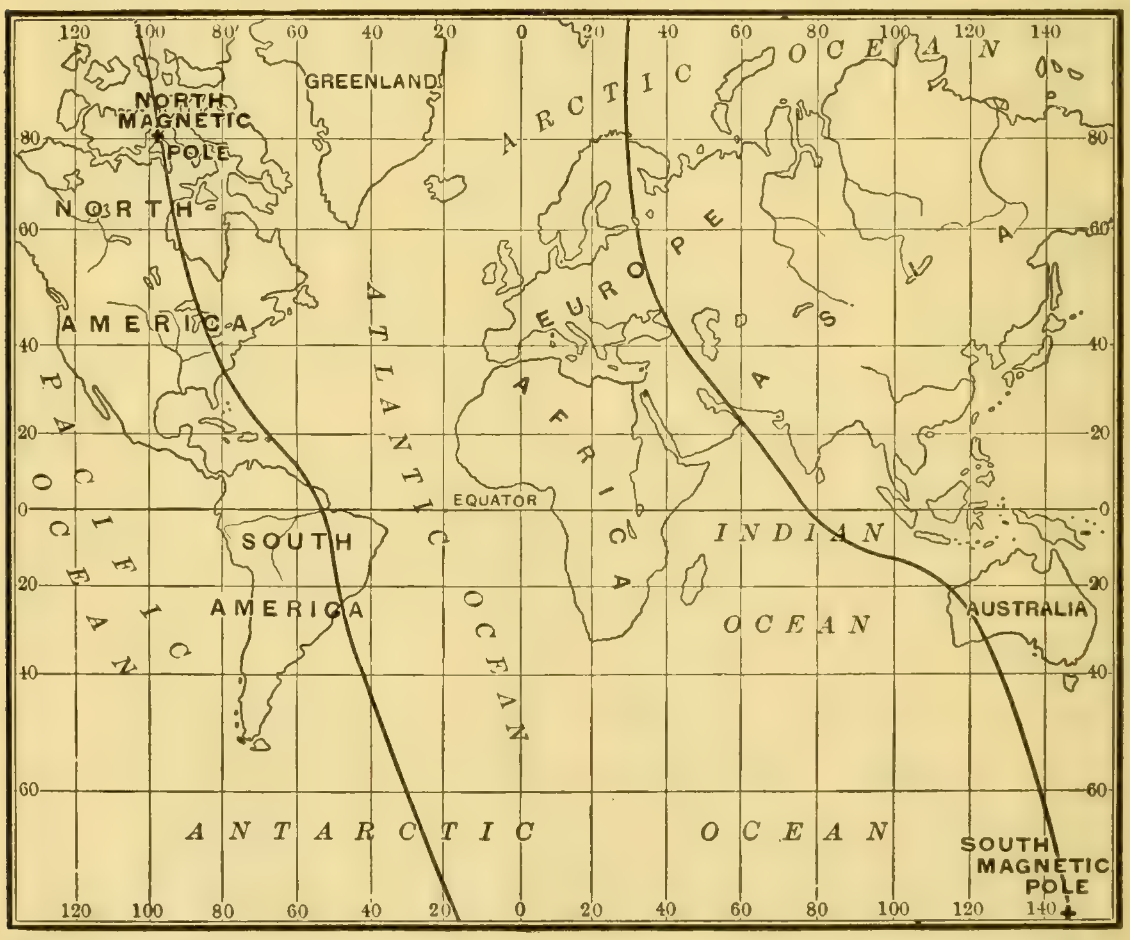


FIGURE 342. — MAP SHOWING THE LOCATION OF THE MAGNETIC POLES AND THE TWO AGONIC LINES.

221. Magnetic Poles of the Earth. — If a dipping needle is moved above a long bar magnet in the direction of the length of the magnet, it will stand vertical when above the poles. By using a horizontal needle as a guide for direction of travel and a dipping needle to determine where to stop, the magnetic poles of the earth have been located. The pole in the northern hemisphere is 73° 31′ N. latitude, 98° 48′ W. longitude. It was first located by Ross in 1831 and redetermined by Amundsen in 1906. The pole in the Antarctic was not found until 1909, when Shackleton located it as 72° 25′ S. latitude, 155° 16′ E. longitude (Figure 342). It will be seen that these poles lie only a little way within the Arctic and Antarctic circles respectively, so that Peary's compass at the north pole must have pointed south.

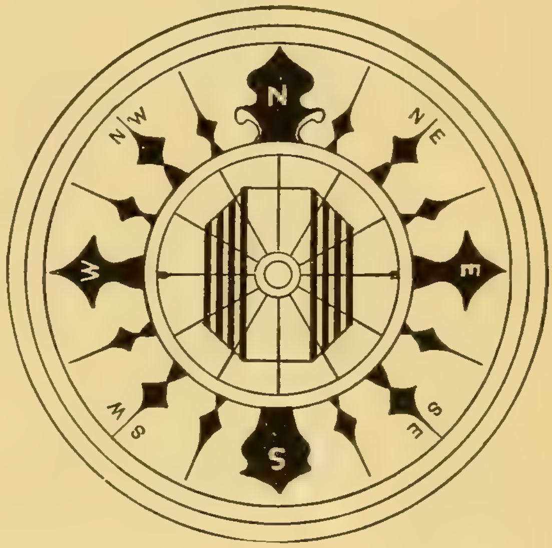


FIGURE 343. — MARINER'S COMPASS (TOP VIEW).

Several needles, on either side of the pivot, are used to secure a strong and uniform compass field. The cord is attached to the needles and turned with them.

222. The Mariner's Compass. — In compasses used for navigation (Figure 343), a card with the points of the compass engraved on it is attached by radial threads to a jeweled bearing resting on a pivot (Figure 344). In the threads are mounted a number of parallel magnetic needles shown as heavy black lines on either side of the pivot in Figure 343. The north point of the card in this compass would point to the magnetic north if it were not for the permanent magnetism of the steel of the ship and the inductive effect of the earth's field on the ship. To counterbalance the effects of

this ship's magnetism, a system of magnets and masses of iron is placed at such points in the immediate vicinity of the compass that their magnetic field will at all times neutralize the disturbing magnetic field of the ship. Many ships now use a gyroscopic compass, which is not magnetic and is unaffected by the iron of the ship.

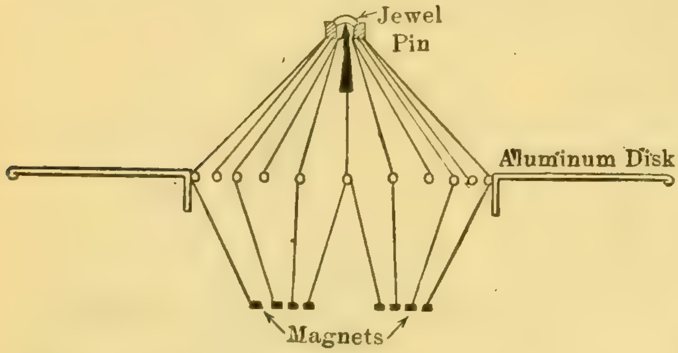


FIGURE 344. — SIDE VIEW OF MARINER'S COMPASS.

The card is on the aluminum disk. The suspension of the card and magnets by cords gives lightness.

223. Changes in the Magnetism of the Earth. — The declination and the dip at any locality are subject to slow changes from year to year. These are recorded in the magnetic surveys already referred to. Small changes occur daily from hour to hour. These are not sufficient to cause important errors except when very accurate readings are required. At times, great and irregular changes in the earth's magnetism take place, causing compass needles to swing irregularly from their normal position. These are called *magnetic storms.* From the fact that magnetic storms usually occur when great disturbances called sun spots are observed in the atmosphere of the sun, it is thought that the sun is in some way the cause of the earth's magnetism.

QUESTIONS

1. Define strength of field; magnetic flux.
2. State four properties of lines of force.
3. What is permeability? Compare the permeability of cast iron and wrought iron.
4. Explain the action of the floating needle in Experiment 91.

5. What kind of magnetic pole is that within the Arctic Circle? What is its approximate location?

6. What magnetic phenomenon disturbed the sailors of Columbus?

7. Define isogonic lines; agonic line; dip; declination.

SUMMARY

Natural magnets, or lodestones, are pieces of magnetite that have become magnetized in their position in the earth's crust, through the influence of the earth's magnetic field.

Poles are the portions of magnets, usually near the ends, in which the force of magnetic attraction is greatest. The north pole is the end of the magnet which, if the magnet is free to move, will point northward; the other pole is the south pole.

Like magnetic poles **repel**; **unlike** poles **attract**. The force of attraction or repulsion increases with the strength of the poles and decreases with the distance between them.

Magnetic substances are those that are attracted by magnets; iron and steel are strongly magnetic, nickel and cobalt are attracted less strongly. Most other substances are practically non-magnetic.

Magnetic induction is the production of poles in a magnetic substance. Two poles are induced in the magnetic substance, by placing it in a magnetic field. The unlike pole is the portion nearest to the inducing pole.

The theory of magnetism states that the molecules of magnetic substances are themselves magnets. When the substance is unmagnetized, the molecules are arranged in a haphazard manner. Magnetization consists in turning the molecules so that their north poles point in one direction. A magnet is weakened by heating or jarring it.

Permanent magnets are made of hardened steel. The best method of magnetizing is to place the steel in a coil of insulated wire and pass an electric current through the coil.

The **magnetic field** is the space surrounding a magnet. Mag-

netic **lines of force** are the directions in which magnetism acts in the field. They are curved lines, emerging from the N pole and entering the S pole, returning to their starting point through the magnet.

Magnetic lines (1) tend to shorten and (2) repel each other; (3) they are closed curves and (4) never cross each other. The number of lines of forces per square centimeter is the measure of the **strength of the field.** The whole number of lines is called the **flux.**

The permeability of a substance is its ability to concentrate lines of force.

The earth acts like a huge magnet, having one pole just north of Hudson Bay and the other in the Antarctic region. The angle made by a horizontal magnetic needle with a true north-and-south line at any place is the **declination** at that place. The angle made by a dipping needle with the horizontal is the **inclination** or **dip.**

Compasses are horizontal magnetic needles pivoted in cases over dials divided into degrees and marked with the points of the compass. Mariner's compasses have their dials attached to the needle and turning with it.

EXERCISES

1. Name four magnetic substances, in the order of their attraction. Name six non-magnetic substances.

2. State, in terms of the theory of magnetism, the difference between an unmagnetized piece of steel and one that has been magnetized.

3. Give four experimental facts that support the theory of magnetism.

4. Draw the magnetic field in each case shown in Figures 329, 331, 332, and 333.

5. How do these figures show the strength of the magnetic fields at different points?

6. Why is it impossible to make a magnet with only one pole?

7. A sewing needle is magnetized and floated on the surface of water in a large dish. What position will it take? Why? Will it move toward the *N* side of the dish? Why?

8. Why should tables in a physical laboratory contain no iron?

9. Will a magnetic needle point in the same direction in New York as in San Francisco? Explain.

10. Why does the government constantly carry on magnetic surveys?

11. Compare the reliability of a simple mariners' compass on an iron ship with that on a wooden ship.

12. Geologists sometimes use a dipping needle in searching for deposits of iron ore. Explain.

13. Why are steel drills used in a vertical position in a machine shop usually found to be magnetized? At which end would you expect to find an *N* pole?

14. Why do surveyors find it impossible to use their compasses on certain days?

15. At which end of a steel umbrella rod would you be likely to find an *N* pole? Explain.

16. If a man could travel to the north pole without his compass varying, what would his path be called?

CHAPTER XVIII

ELECTROMAGNETISM

Most of the elementary facts of magnetism given in the preceding chapter were set forth by Gilbert in 1600. During the latter part of the eighteenth century there were made a great many discoveries in electricity, but it was not until about 1820 that Oersted discovered that every electric current was surrounded by lines of magnetic force. We will repeat his experiment and others made shortly afterward,

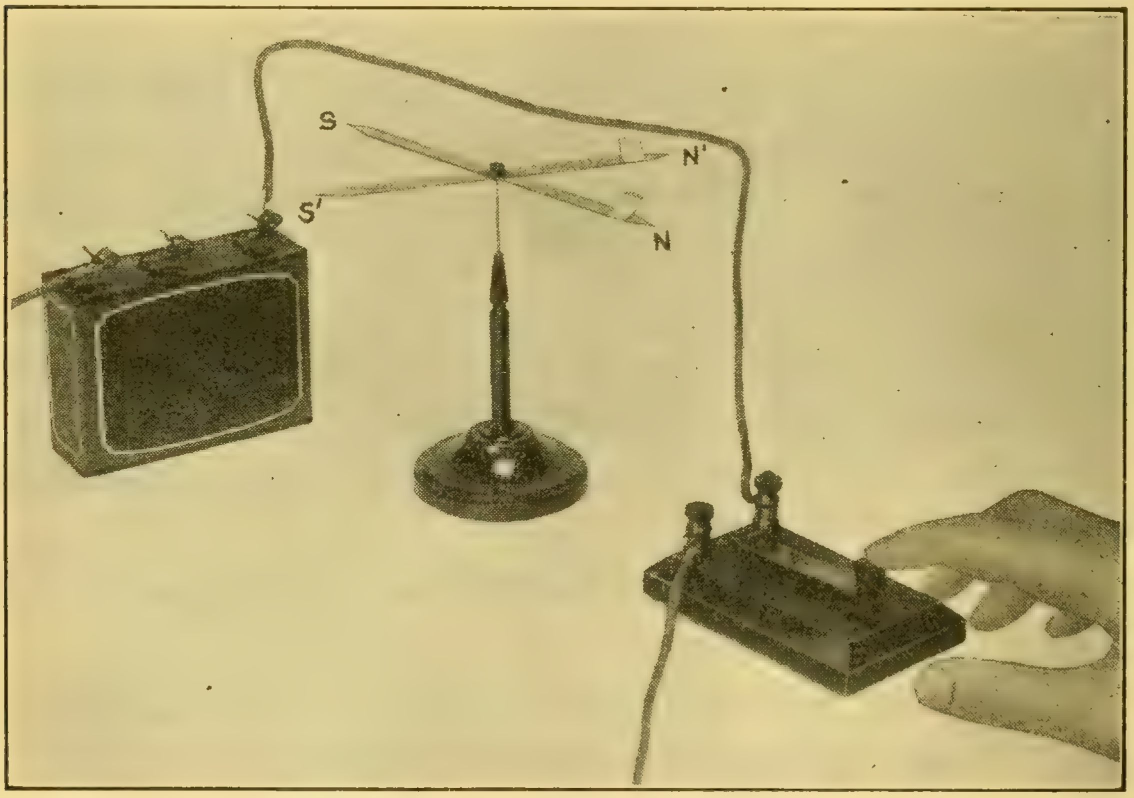


Figure 345. — Oersted's Experiment.

The wire from the battery runs from south to north, above the magnetic needle NS. When the switch is closed, current flows. The needle takes the position $N'S'$, showing a magnetic field around the current.

224. Magnetic Field around a Conductor Carrying a Current. —

EXPERIMENT 95. — Over a magnetic needle and parallel to it place a wire connected to a dry cell through a key (Figure 345). Close the circuit and observe the behavior of the needle. *Result?* Place the wire under the needle and again send the current through it. *What difference do you note in the behavior of the needle?* Reverse the direction of the current through the wire. *Result?*

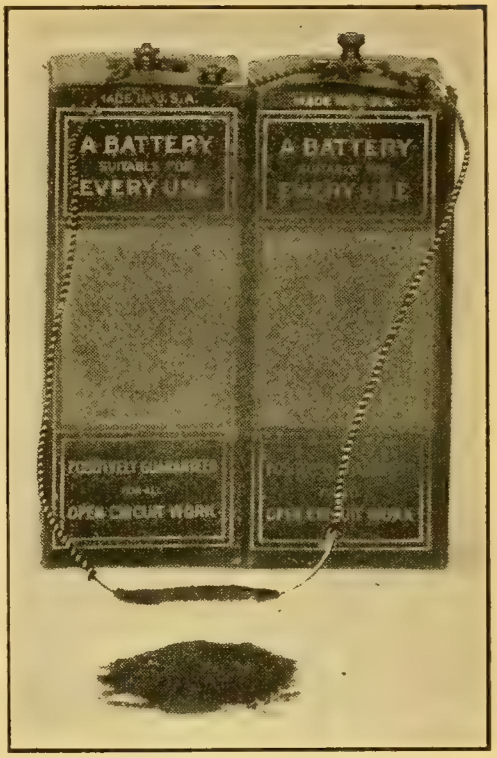


FIGURE 346. — Iron filings cluster around the wire when the current flows, showing lines of force.

EXPERIMENT 96. — Connect a piece of bare #18 wire through a switch to a circuit that will send a current of several amperes through the wire. Dip a horizontal section of the wire into a pile of iron filings. Close the switch and raise the wire out of the pile of filings (Figure 346). *Result?* Open the switch and observe the filings. *Is it the attraction of the wire for the filings or the passage of the current that causes the filings to group themselves around the wire?*

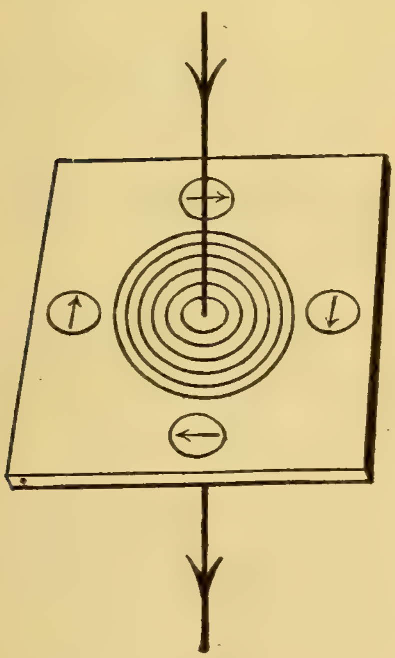


FIGURE 347. — The circles of filings show the shape of the lines around the wire, and the needles show their direction.

EXPERIMENT 97. — Pass the same wire used in the previous experiment up through a horizontal piece of cardboard (Figure 347). Place a small compass near each edge of the cardboard. Close the switch and sprinkle a few iron filings on the card from a shaker. Tap the card lightly. *What is the form of the magnetic lines of force surrounding a conductor that carries a current?*

These experiments show clearly that, when a current is passing through a wire, magnetic lines of force surround the wire in concentric circles. The behavior of the compass

needle shows that the direction of these lines depends on the direction in which the current is passing through the wire. These facts are of the greatest importance, because they enable us to produce and control magnetic fields for a great variety of purposes.

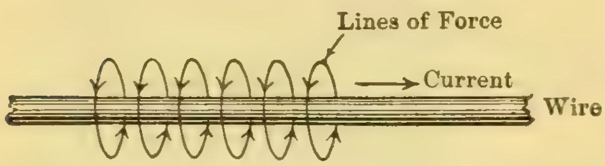


FIGURE 348. — The fingers would encircle the wire in the direction of the arrows.

225. Direction Rule. — As it is desirable in many cases to know the direction of the lines of force produced by a current, it is well to learn a simple rule connecting the direction of the current and the direction of the lines of force around it. Such a rule is the following:

Grasp the wire with the right hand, so that the thumb is pointing in the direction in which the current is flowing; then the fingers will point in the direction in which the lines of force encircle the wire (Figure 348).

226. Magnetic Field of a Solenoid. — A *solenoid* is a coil of wire wound like a coiled door spring. It may have a single layer or many layers. We will first experiment with a solenoid of a single layer.

EXPERIMENT 98. — Wind a solenoid through holes in a stiff cardboard like that shown in Figure 349. The turns should be about half an inch apart. Connect this to the circuit used in Experiment 96. Sprinkle iron filings on the card, and tap it to allow them to arrange themselves. Notice that, while there are a few small circles around each wire, the repulsion of the lines of force causes most of them to arrange themselves in nearly straight lines extending lengthwise through the solenoid, entering at one end and leaving at the other.

The closer the turns in a solenoid, the greater the number of lines extending through the center, so that the magnetic field of a solenoid is like that of a bar magnet, with poles at

the ends of the solenoid (Figure 349). A solenoid, carrying a current, is an *electromagnet.* This may be shown more clearly by wrapping a piece of soft iron in paper and slipping it through the part of the solenoid under the cardboard. The iron concentrates the lines of force (§ 217) and the iron

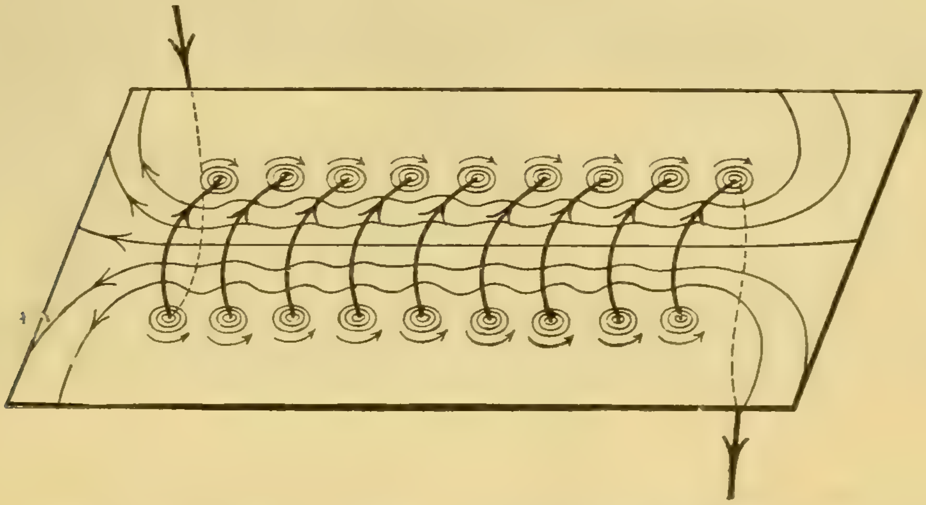


FIGURE 349. — When the current is passing the solenoid acts like a bar magnet. Note that the lines do not cross and their direction is that given by the right-hand rule.

filings outside the solenoid show a field like that surrounding a bar magnet.

227. Electromagnets. — The experiment with the solenoid teaches us the essential parts of an electromagnet. These are: a coil carrying a current and having an iron core (Figure 350) — "coil, current, and core." Since the magnetism of soft iron is *temporary,* an electromagnet with a soft-iron core loses most of its magnetism when the current is turned off. This makes electromagnets far more useful than permanent magnets, for they can be magnetized or demagnetized at will by closing or opening a switch. When we realize that telegraph systems, electric motors, electric bells, telephone receivers, door openers, and all other devices in which electricity is used to produce motion or do work depend on the

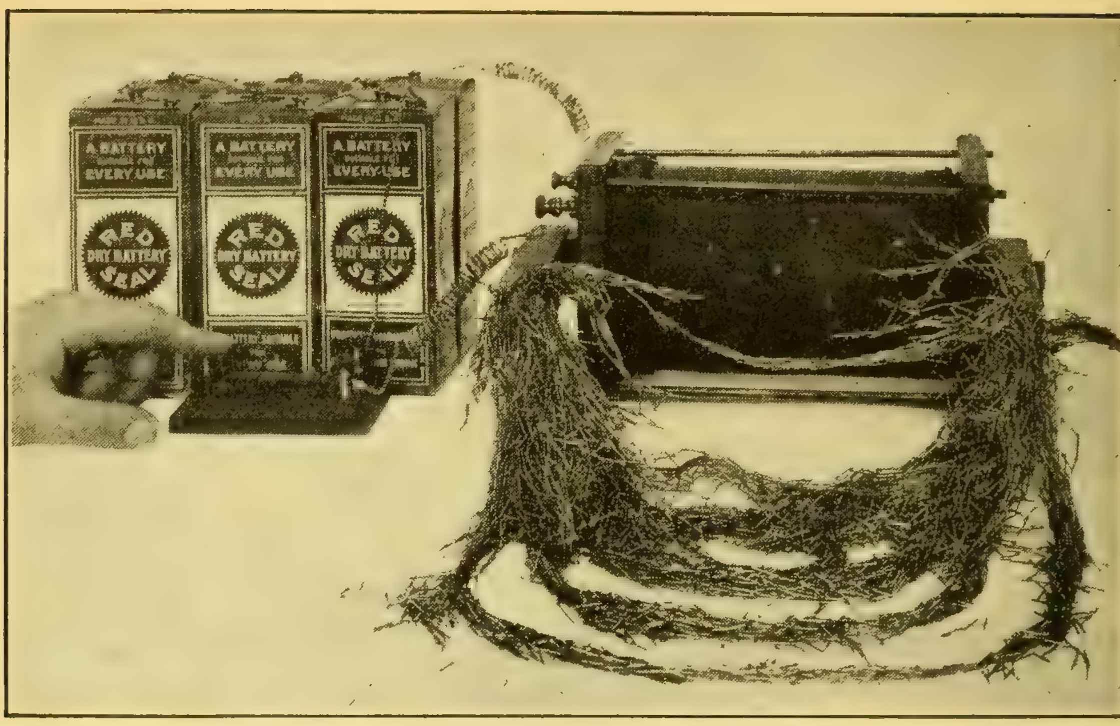


FIGURE 350. — ELECTROMAGNET.

The poles were dipped in a box of nails while the current was passing, and the nails formed chains along the lines of force.

action of electromagnets, we see the tremendous importance that Oersted's discovery has had on our everyday life.

228. Polarity of Electromagnets. — We have already seen that the direction of the current determines the direction of the lines of force. The polarity of an electromagnet is best remembered by another "right-hand" rule:

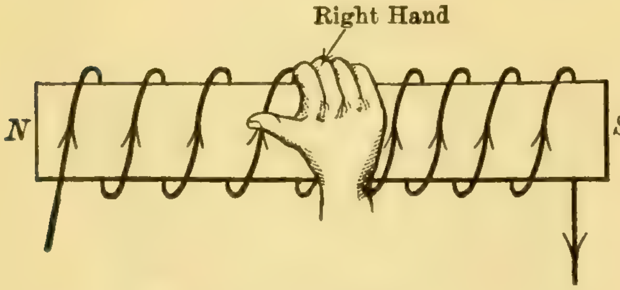
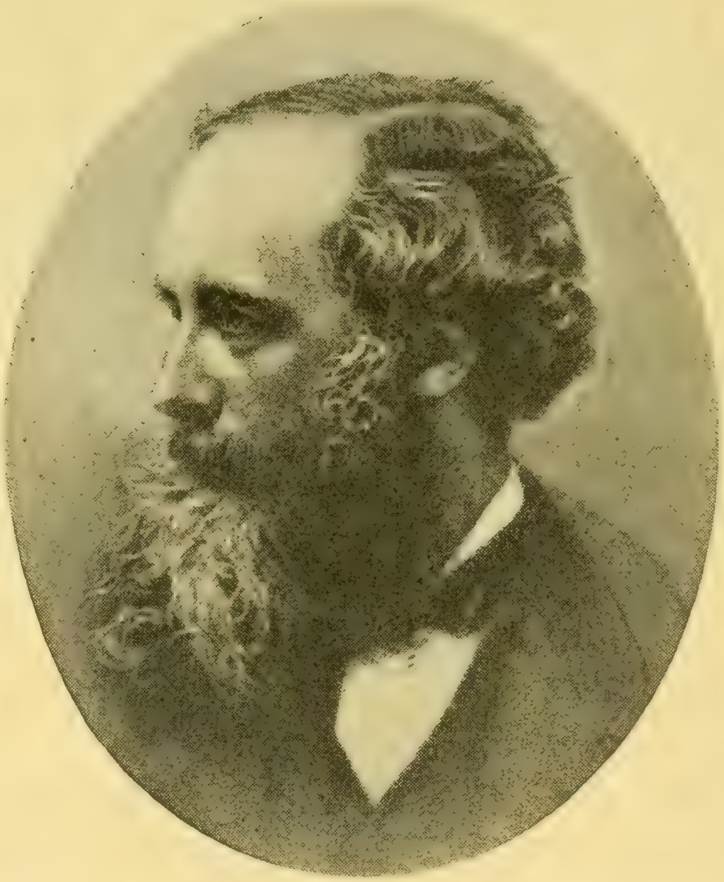


FIGURE 351. — RIGHT-HAND RULE FOR ELECTROMAGNET.

Grasp the coil with the right hand so that the fingers extend in the direction of the current; the extended thumb will point toward the north pole (Figure 351).

It is important to remember that the *direction of the current* and not the end at which it enters, *fixes the polarity of the*



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James Clerk-Maxwell (1831–1879). More recent scientists find less new things left to discover and must therefore turn their attention to the extension and explanation of the discoveries of their predecessors. Maxwell, a mathematical physicist of first ability, gave form to the theory that all magnetic and electrical phenomena, together with other forms of radiant energy, are disturbances of the ether. His equations gave certainty to the ether theory and from them Hertz was led to the assumption and proof of the "wireless" waves which transmit the radio messages of to-day.

magnet. Practical magnets have many layers of wire, but the current passes through all the wires in the same direction, and they all contribute to the strength of the magnet.

229. Strength of Electromagnets. — Since each turn of wire produces its own lines of force, the greater the number of turns, the stronger the magnet. The lines are caused by the current's flowing; doubling the current doubles the number of lines. The strength of an electric current is expressed in *amperes.* The magnetic strength of a solenoid without an iron core, then, is proportional to the number of turns and to the number of amperes. The product of the number of amperes multiplied by the number of turns is called the *ampere-turns.* The number of ampere-turns determines the strength of the magnet. This means that a solenoid of 100 turns through which 5 amperes of current flow will have the same strength as one of 5 turns carrying 100 amperes, or one of 20 turns carrying 25 amperes, for in each case there will be 500 ampere-turns. This fact causes us to use many turns when we have only a small current in the circuit, and few turns when the current is large.

An iron core in a solenoid concentrates lines of force that would otherwise leak out through the air. Therefore an iron core always strengthens the magnet. With a given number of ampere-turns, and a core filling the solenoid, the strength of the magnet depends on the permeability (§ 217) of the iron. Wrought iron is more permeable than other forms of iron and so pure wrought iron is selected when the strongest magnet is desired. Soft steel is also highly permeable and is therefore frequently used.

The strength of an electromagnet is proportional to the number of ampere-turns and to the permeability of the iron core.

QUESTIONS

1. What is the shape of the magnetic lines of force around a wire carrying a current?

2. State a rule by which the relation between the direction of the current and that of the lines of force may be remembered.

3. What is a solenoid? Describe its magnetic field when it is carrying a current.

4. How does the introduction of an iron core into a solenoid affect the shape and number of lines of force in the field of the solenoid?

5. State the essential parts of an electromagnet.

6. Give a rule for the polarity of an electromagnet.

7. Explain the meaning of *ampere-turns;* of *permeability.*

8. State the three factors that determine the strength of an electromagnet.

230. Kinds of Electromagnets. — Electromagnets are made in different shapes, according to the use for which they are designed. A very common form is the *horseshoe* elec-

FIGURE 352. — The horseshoe electromagnet is very strong for its size.

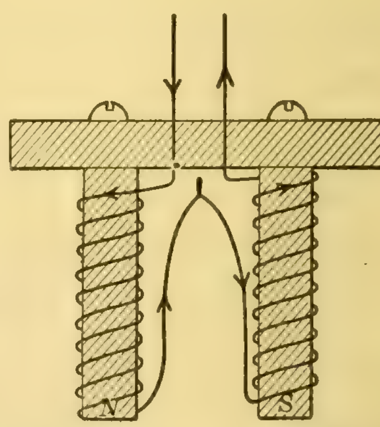


FIGURE 353. — The yoke is across the top.

tromagnet (Figure 352). It would be very inconvenient to wind coils of wire on the ends of a U-shaped core of iron. So two spools of wire are wound upon straight iron cores (Figure 353); these coils are so connected that the current will pass around them in opposite directions. The cores are then at-

tached very closely to the ends of a bar of soft iron called the *yoke*. When a current is passed through the coils, the free ends of the cores will be opposite poles, because the current passes around them in opposite directions. Horseshoe electromagnets of this type are used for a great variety of purposes, including the electric bell and buzzer, the telegraph sounder and relay, and the telephone receiver.

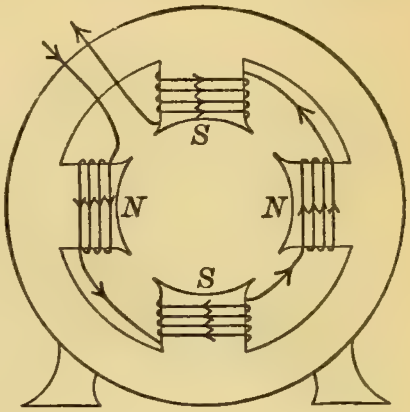


FIGURE 354. — FIELD MAGNET OF DYNAMO.

In motors and generators, the yoke connecting the poles is usually a ring of cast steel (Figure 354). These *field magnets* often have many poles, alternately N and S. The *lifting magnet* is another special form of horseshoe magnet. The coil is wound on a short, straight core (Figure 355), and this is bolted to the center of a bowl-shaped casting of soft steel. When current is passed through the coil, lines of force from the inner end of the core extend through the iron to the edges of the bowl, then through the air to the core again. This gives a very strong, concentrated magnetic field. When such a magnet is placed on a piece of steel or iron, and the current turned on, the magnet holds the iron with great force (Figure 356). When the current is turned off, the iron is released. Lifting magnets may be made of almost any size and strength, and when suspended from cranes, make it possible to lift great

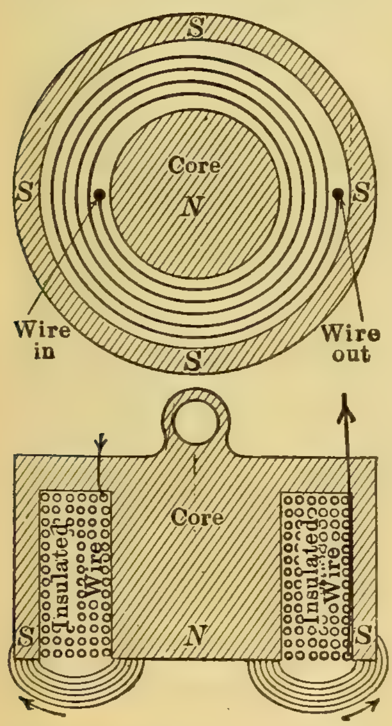
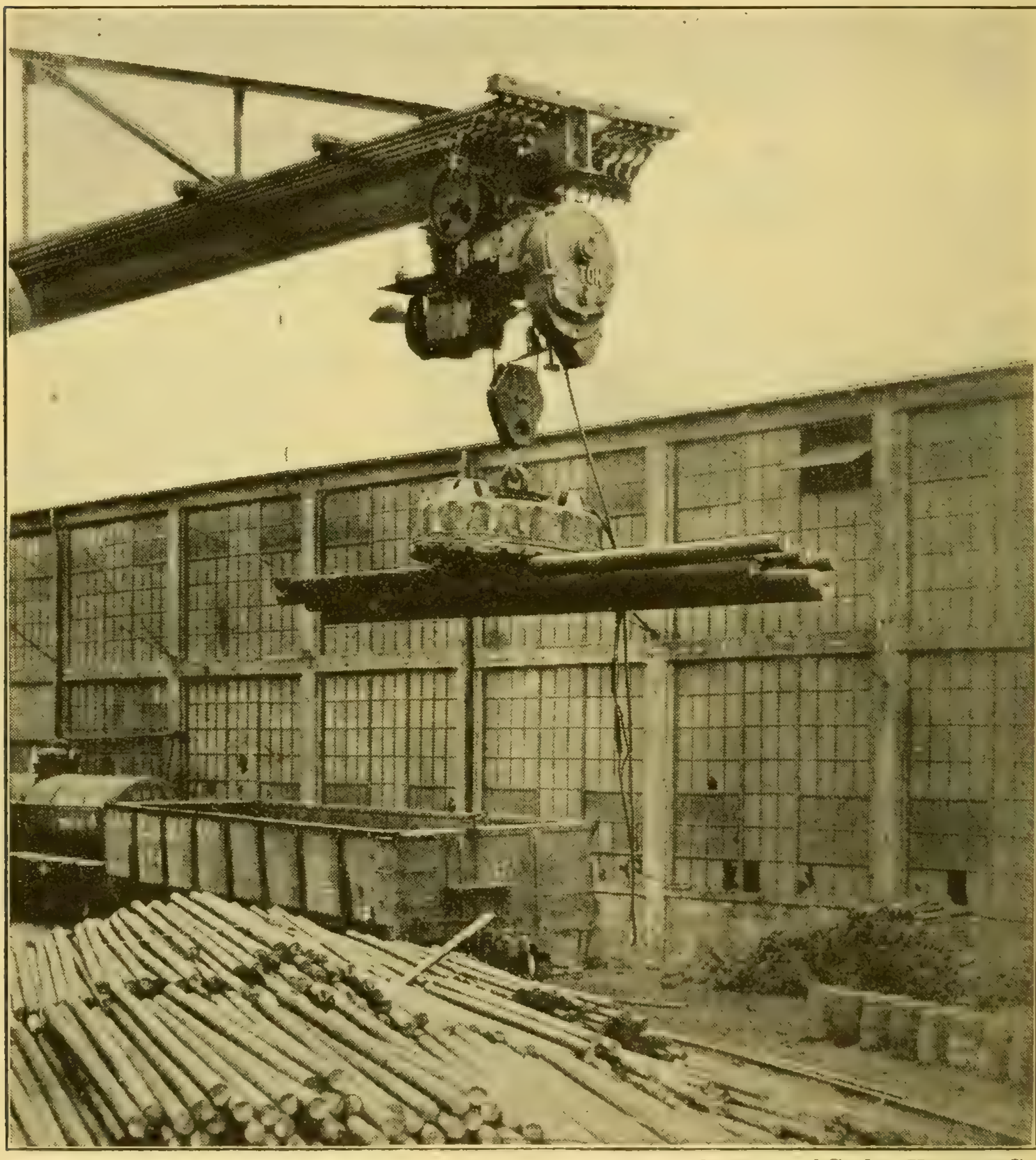


FIGURE 355. — LIFTING MAGNET.
Bottom view and vertical section.

weights of iron and steel, without the time and labor necessary to surround these objects with chains. The form of core and casing may be varied, so that the magnet may be



Courtesy of Cutler-Hammer Co.

FIGURE 356. — LIFTING MAGNET IN USE.

The steel rods, weighing 2800 lbs, are being loaded into the car by the derrick. The magnet is used instead of putting chains around them.

used with objects of different sizes and shapes, ranging from nails in a keg to a locomotive.

The lifting effect of a magnet depends not only on the

number of ampere-turns and the permeability of the core, but also on the shape of the pole-pieces. Making the cross section somewhat smaller at the lifting ends concentrates the lines of force and gives greater lifting effect.

231. Circuit-Breakers. — It is always necessary to prevent an electric circuit from carrying too much current, because of danger from the heating effect produced (Chapter XXI). A form of circuit-breaker widely used on switchboards depends on the action of a "sucking coil." This apparatus is best understood by a simple experiment.

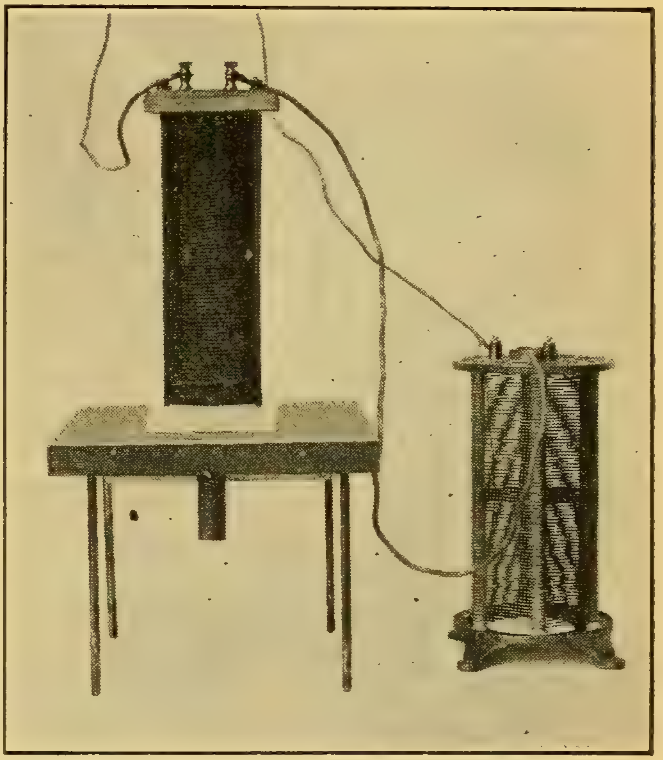


FIGURE 357. — SUCKING COIL.

The bar has been lifted from the table into the strong field of the hollow magnet. The rheostat at the right limits the current.

EXPERIMENT 99. — On a fiber or cardboard tube, open at both ends, wind enough wire so that the available current will make a strong magnetic field. Mount this coil vertically on a firm base, raised about two thirds the height of the coil above the table, with the end of the tube projecting through the base, which is elevated some distance above the table. Stand on the table a bar of soft iron a little smaller than the opening in the tube, with one end in the lower end of the tube. Turn on the current, and observe the behavior of the iron (Figure 357). The effect is due to the tendency of iron to move from a weak magnetic field into a strong magnetic field, a tendency shown in all cases of magnetic attraction.

In the circuit-breaker (Figure 358), the current is sent through a sucking coil of heavy wire or bar copper like that

just described, provided with an iron core free to move. The switch that closes the circuit is usually a strong flat brass spring which is held closed by a latch. In the drawing a spiral spring is shown instead of the flat spring. When more current flows than the circuit can safely carry, the core is drawn up into the coil, and, as it comes up, strikes a projection of the latch, releasing the spring and opening the circuit. By adjusting with a screw the distance that the core must be lifted, the breaker may be set for any desired current.

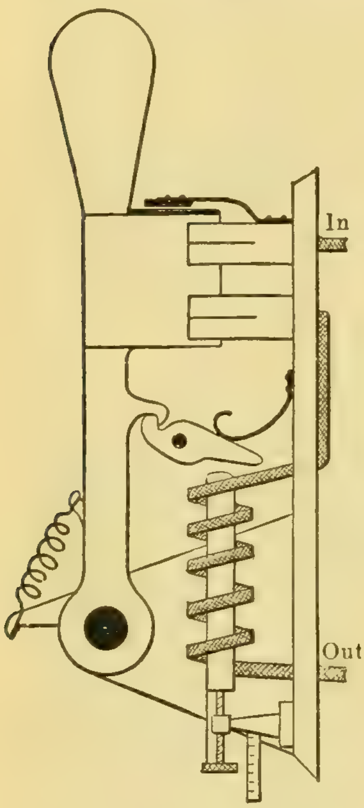


FIGURE 358. — CIRCUIT-BREAKER.

The core is set for the current desired by the screw at the bottom.

232. Electric Bell. — This is one of the most familiar applications of the electromagnet. In the common jingle bell, a horseshoe electromagnet is used (Figure 359). The current enters the magnet from one of the binding posts of the bell, and passes around the magnet coils. The farther end of the magnet coil is connected to the contact screw. Opposite the poles of the electromagnet is a soft-iron armature, to which the hammer is attached. This armature is held in position by a spring, attached to the iron base of the bell frame. A flat spring along the side of the armature away from the magnet forms a tongue, which rests against the contact screw when the bell is silent. The second binding post is attached without insulation to the iron base. The bell works equally well if the direction of the current is reversed.

When the circuit is closed by means of the spring switch

or *push-button,* current flows from binding post to binding post through the magnet, contact point, tongue, armature, armature spring, and bell frame. The armature is attracted and the hammer strikes the bell. But in so doing, the tongue leaves the contact point and the circuit is broken. This action demagnetizes the magnet, and the armature spring pulls the armature away from the magnet poles, allowing the tongue to strike the contact point. This again closes the circuit and the whole process is repeated. The armature therefore continues to vibrate as long as the circuit is closed, and the hammer makes repeated strokes against the bell.

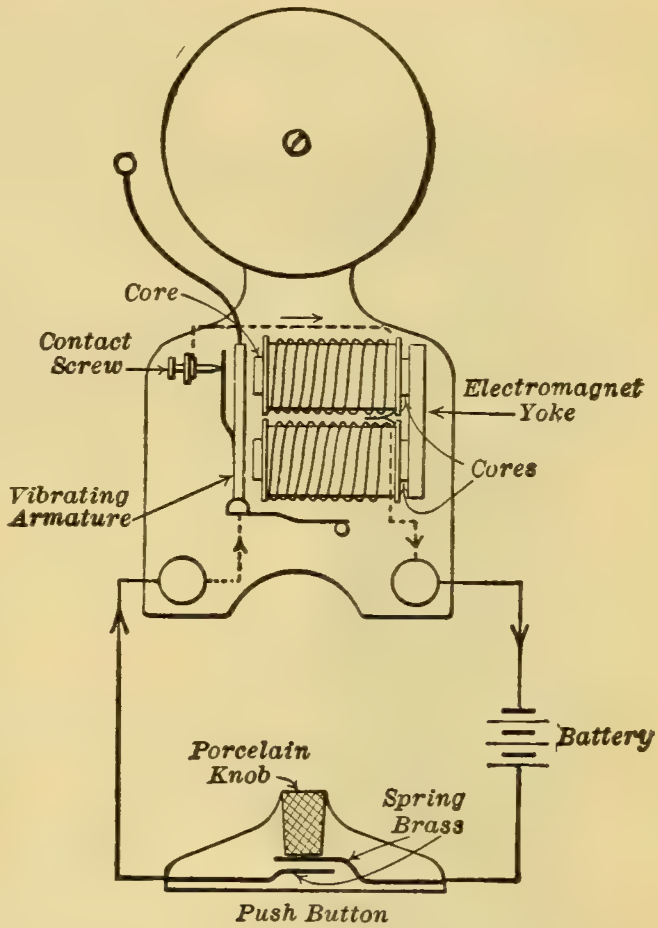


FIGURE 359. — ELECTRIC BELL.
The push button is shown in section.

The "buzzer" is made in the same way, except that there is no hammer or gong. The action is the same and the noise is due to the vibration of the armature against the contact point. If a single-stroke bell or gong is desired, the second binding post is connected directly to the contact point, and no current passes through the armature. The armature will not be released until the

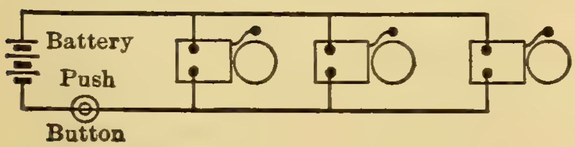


FIGURE 360. — Bells should be connected in parallel.

circuit is opened. If several bells are to be rung from the same push button, they should be connected as in Figure 360.

In an *annunciator,* one side of each push button is connected to a common wire, in which the battery is inserted and which leads to one terminal of the bell. The other side of each push button is connected by its own wire to an electromagnet in the annunciator case and then to the other terminal of the bell, as shown in Figure 361. Opposite each electromagnet is a pivoted armature, with a latch that holds up out of sight a little frame containing a number or name that shows where the push button is located. When a button is pushed, a current flows through the corresponding magnet, the armature is attracted, unlatching the frame, and the labeled frame drops into view. Means are provided for putting up the frame again, after the call.

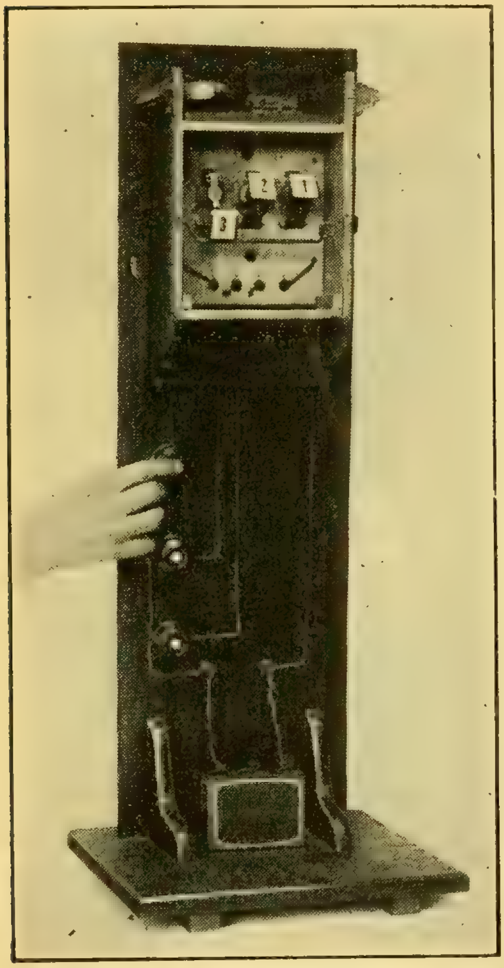


FIGURE 361. — ANNUNCIATOR.

The wire from each button leads to its electromagnet and then to the bell on the top.

233. Telegraph Systems. — The electric telegraph was the earliest important application of the electromagnet, but it was twenty-five years after Oersted's discovery before Samuel F. B. Morse sent the first message in 1844 over the line from Washington to Baltimore.

The *telegraph sounder* is very similar in its action to the single-stroke bell just described. It has a vertical electro-

magnet of the horseshoe type (M, Figure 362). A soft-steel armature (A) is suspended above the poles of the magnet by means of a rockerarm (R). This rocker arm is pivoted to a post near one end of the sounder, and held away from the magnet by a spring (S). When a current is sent through the magnet, the armature is attracted to the poles, and the outer end of the rocker arm is brought down suddenly against the anvil (V), making a click. When the circuit is opened, the spring brings the rocker arm up until it strikes a stop projecting from the top of the anvil, making a different sound. When the circuit is closed a very short time, the *interval* between clicks against anvil and stop is called a *dot;* when the time is longer, it is called a *dash.* These names come from the fact that in the original instruments the rocker arm carried a pen and made short or long marks on a moving paper tape.

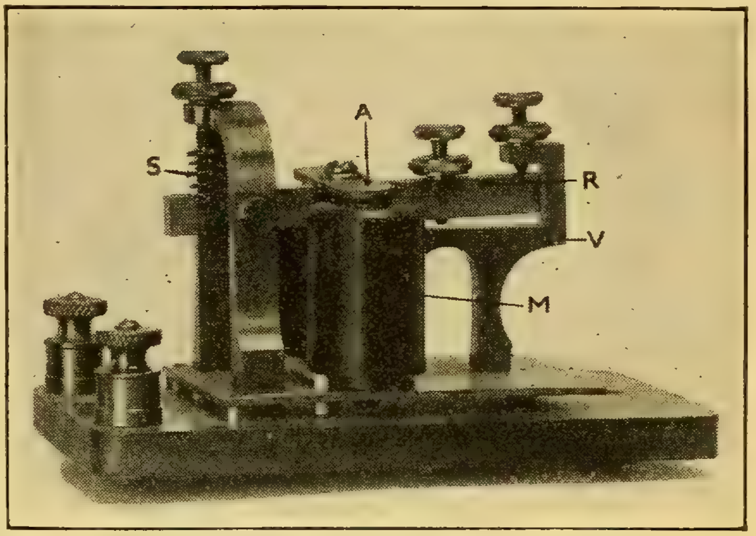


FIGURE 362.—TELEGRAPH SOUNDER.

The set screws regulate motion of rocker arm according to current furnished and sound desired.

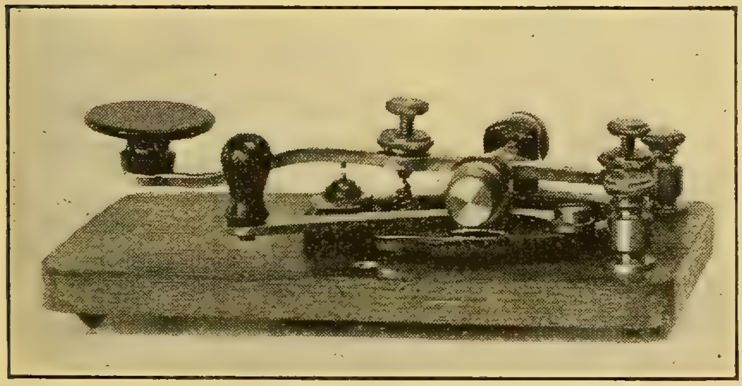


FIGURE 363.—TELEGRAPH KEY.

The lever in front is drawn out when sending, and pushed in, short-circuiting the key, when receiving.

A special form of switch, called a *telegraph key* (Figure 363), is used in sending messages. The key consists of a metal lever, pivoted between two supports projecting from its metal base. From the under side of the key near the front a contact point projects downward. Immediately below this point is a similar point, carefully insulated from the base. The points are kept from touching by a spring under the key in front of the pivots. One terminal of the circuit is connected to the insulated point, the other to the metal base of the key. When the key is depressed by the operator's finger, the points are brought into contact, and current from the line battery flows through the metal base, pivots, lever, and contact points to the sounder, operating the latter as described above.

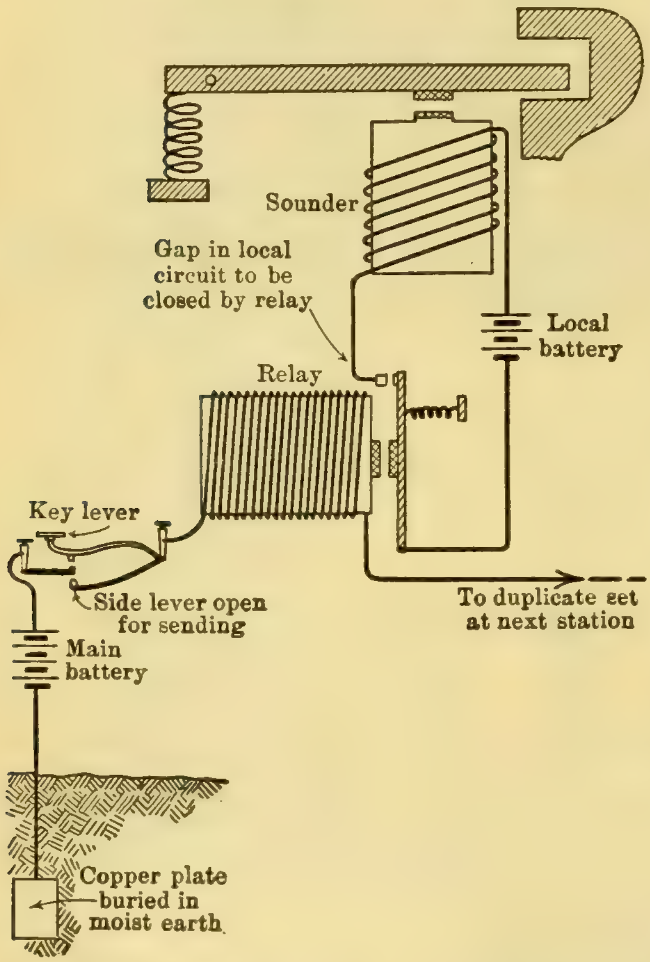


FIGURE 364. — ONE END OF A TELEGRAPH LINE.

The line wire is shown at the bottom. This leads over the poles to all the stations on the line. At each is a key, relay, local battery, and sounder.

Dots and dashes are made by depressing the key for short and long times respectively.

Since all the keys and all the sounders in a telegraph circuit are connected *in series* (Figure 364), that is, so that the entire current flows through each, some means must be pro-

vided for closing the circuit through every other key except the one from which the message is being sent. This is accomplished by a *side lever,* shown in the front of the picture. This closes the circuit between the base and a spring attached to the insulated contact point. When an operator is sending, he swings this lever outward, opening the circuit through his key; when he finishes, he *short-circuits* his key by swinging the lever against the insulated contact point.

The current for a telegraph circuit is usually furnished by line batteries, placed at the two stations at the end of the line (Figure 364). Generally all the stations are connected by a single wire, and at the terminal stations the two ends of this wire are buried in moist earth, so that the current returns through the earth, which is a good conductor.

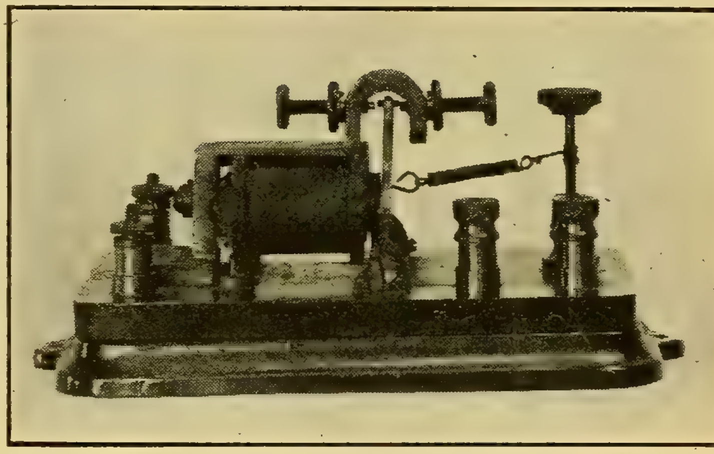
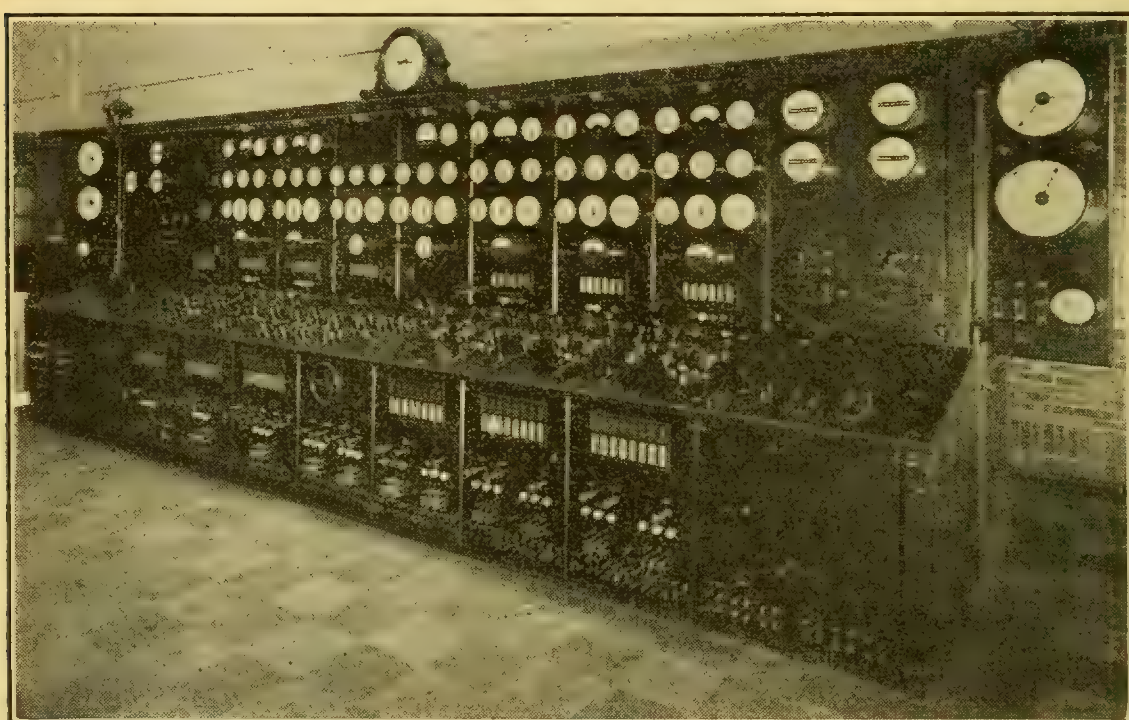


FIGURE 365. — TELEGRAPH RELAY.

The line is connected to posts at left end. One right post is connected to armature and the other to the curved post at center. Armature is shown resting against an insulated stop.

234. Relays. — On account of the great length of telegraph circuits, very large batteries would be required if enough current was sent over the line to pull down the armatures sharply against the force of their springs. So in long circuits the sounders are not connected directly in the line, but *relays* are used instead. *A relay is an electrically operated switch, requiring very little current.* It has a horizontal electromagnet, wound with a great number of turns of very fine wire (Figure 365). Its

armature is vertical, pivoted at the bottom, and held away from the magnet by a very weak spring. The current of the line passes through the magnet. On account of the large number of turns and the slight force necessary to move the vertical armature, an exceedingly feeble current will cause the magnet to draw the armature toward it. When no cur-

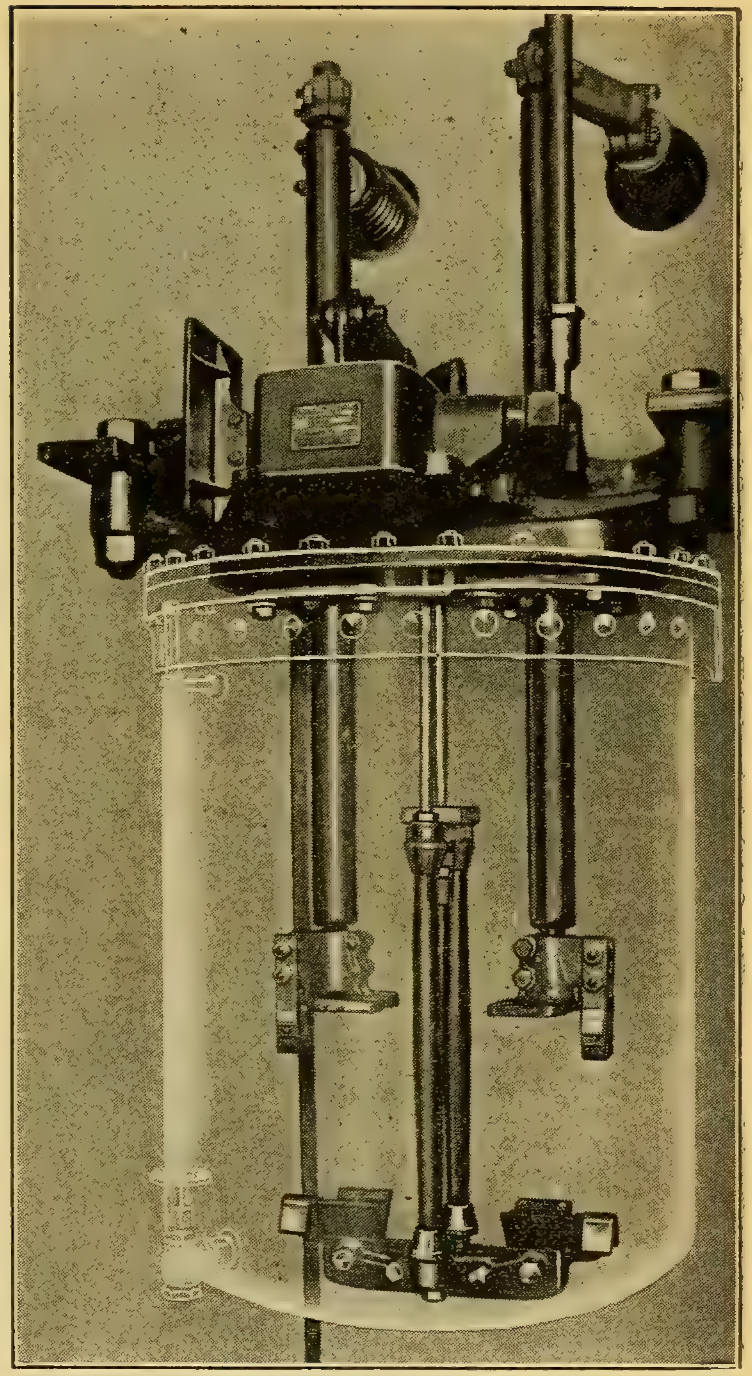


Courtesy of United Electric Co., N. Y. C.

FIGURE 366.— POWER HOUSE CONTROL ROOM.

Each small push button switch on the inclined table closes the circuit to a magnet or motor, which closes an oil switch (Figure 367) in one of the main distributing circuits.

rent is passing, the relay armature rests against an insulated stop. The base of the armature is connected to one binding post, and a second binding post is connected to the vertical curved bar, having an adjustable contact. A *local battery* and the sounder are connected to these two binding posts. When the line current flows through the magnet of the relay, a contact point on the armature of the relay touches a contact point on the vertical stop. Therefore the



Courtesy of United Electric Co., N. Y. C.

FIGURE 367. — OIL SWITCH.

The magnet that operates the switch is at the top. The switch is open. The iron tank for the oil is shown as if transparent so as to make the switch visible.

relay acts as a key in the local circuit, that is, it closes the only gap in this circuit; current from the local battery then flows through the sounder, causing it to click.

The use of the relay principle is not limited to the telegraph, but is applied in a great number of cases, where it is desirable to close a switch from a distance by the use of an electromagnet. Such a system is called a *remote-control* system. It is widely applied in large power houses where small switches (Figure 366) and small currents are used at the main switchboard to energize electromagnets or motors, which open and close large switches (Figure 367), conveniently placed in the main distributing lines.

QUESTIONS

1. Draw a bar electromagnet; a horseshoe electromagnet. In each case indicate the direction of the current by arrows and mark the poles.

2. What is the advantage of a horseshoe electromagnet over a bar electromagnet?

3. Draw a lifting magnet. Why is this form adopted?

4. State the factors on which the lifting power of an electromagnet depends.

5. What is the purpose of a circuit-breaker? What are its essential parts?

6. In an electric bell, state the use of (*a*) the magnet coil; (*b*) the armature; (*c*) the spring.

7. What is a "buzzer"? How does a single-stroke bell differ from a "jingle bell"?

8. Explain how the "drop" in an annunciator is operated.

9. Name the essential parts of a simple telegraph system of two stations. Give the use of each part.

10. In the telegraph sounder, what is the use of: (*a*) magnets; (*b*) armature; (*c*) rocker arm?

11. How are *dots* and *dashes* produced?

12. What points does the *side lever* of the key connect when closed? Why is it used?

13. Why are the ends of a telegraph line connected to the earth?

14. State two ways in which the relay differs from the sounder.

235. Electric Motor. — Any one examining an electric motor is immediately struck with the fact that it is largely composed of insulated wire, wound on various pieces of iron, in other words, that it consists largely of electromagnets. These electromagnets consist: (1) of the *field magnets*, whose windings are placed on *pole pieces* projecting from the stationary outer frame of the motor; (2) of the *armature*, an iron core mounted to rotate within the pole pieces and having windings running lengthwise on it (Figure 368). As

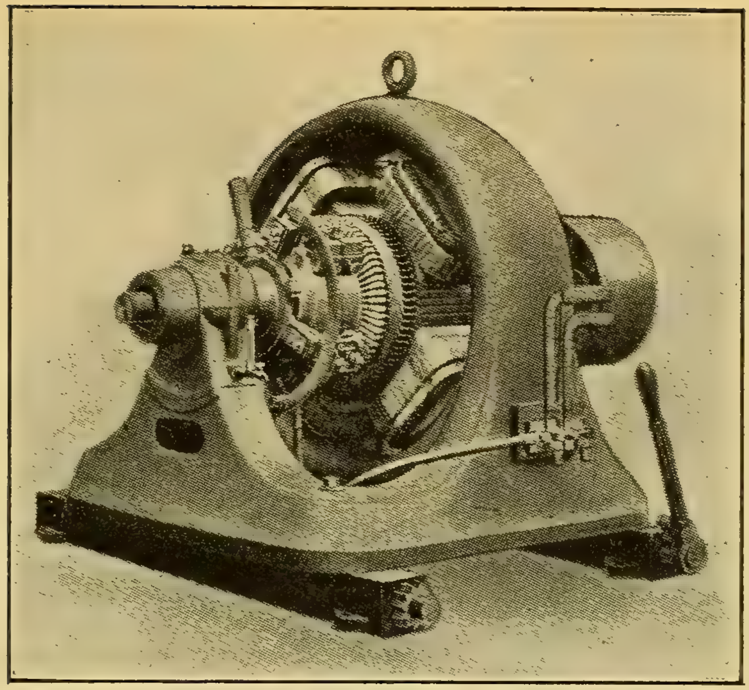


FIGURE 368. — ELECTRIC MOTOR.

The field poles with their windings show clearly. The cylinder rotating between them is the armature. The heavy blocks at the left end of the armature are carbon brushes resting on the commutator.

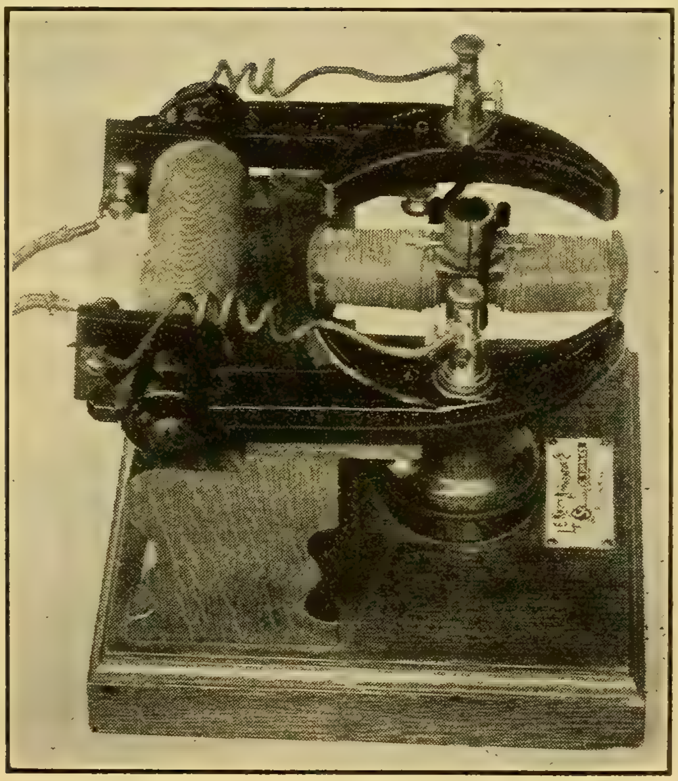


FIGURE 369. — DEMONSTRATION MOTOR.

The field is a bar magnet with curving pole faces and the armature is a bar magnet with a two-piece commutator. The brushes are flat brass springs.

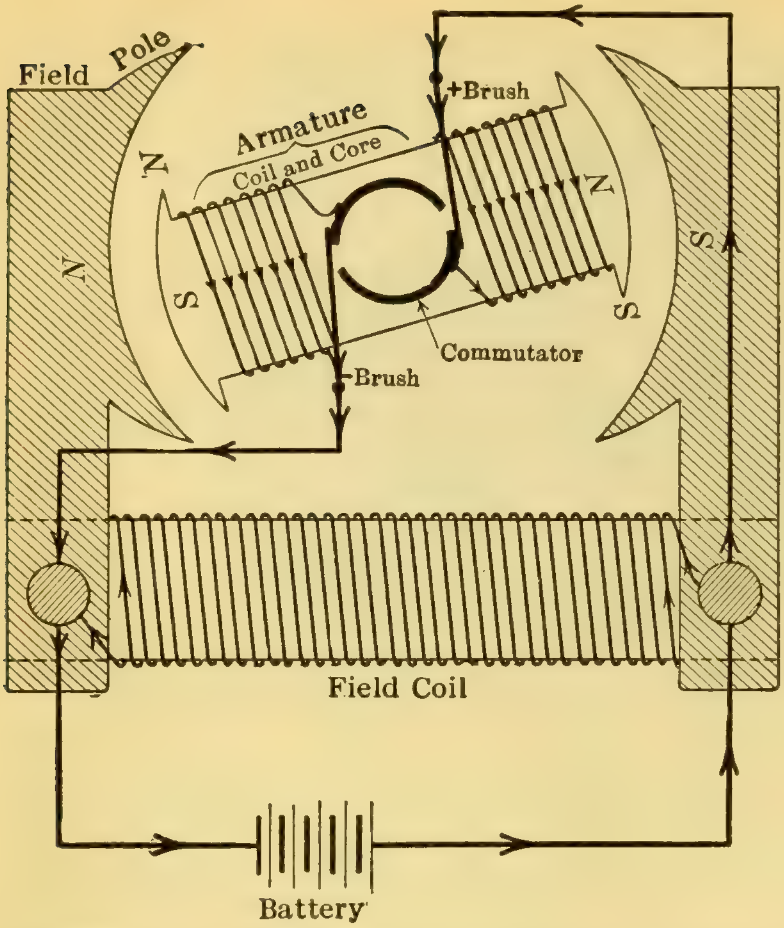


FIGURE 370. — DEMONSTRATION MOTOR, CIRCUIT DIAGRAM.

the commercial motor is somewhat complicated, let us first study a greatly simplified form of motor, shown in Figure 369 and in diagrammatic form in Figure 370. This consists of a field magnet with two pole pieces (N) and (S). A bar electromagnet is pivoted between the pole pieces. The coil on this armature is wound from end to end, and the two ends of the wire are connected to the two halves of a split brass ring. The halves are mounted on the shaft and insulated from each other and from the armature. The insulated split ring (Figure 371) is called the *commutator* (direction changer).

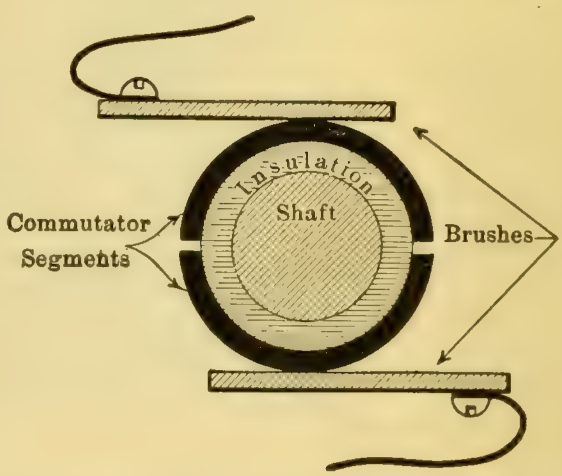
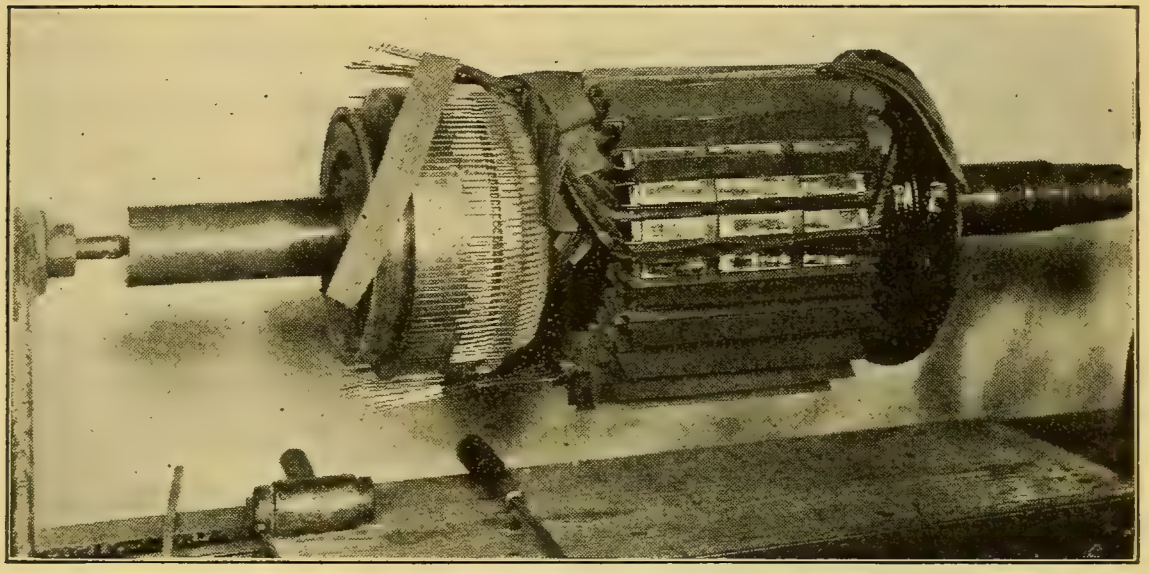


FIGURE 371. — SIMPLE COMMUTATOR AND BRUSHES.

Current furnished from a battery to the field magnet produces poles N and S. Now if current is also sent into the armature through pieces of spring brass, called *brushes,* that rest on the commutator halves or *segments,* the arma-

ture will also become a magnet while the current is flowing. Unlike poles of the armature and the field magnet will attract each other, and the armature will turn. When the armature has made a quarter turn from the position shown in Figure 369, the commutator segment that has been in contact with the + brush will leave it and come in contact with the − brush. This causes the current in the arma-



Courtesy Westinghouse Electric Machine Co.

FIGURE 372. — ARMATURE IN PROCESS OF WINDING.

Armature coils are laid in slots of the armature core, from which they are insulated by fiber sheets. The ends of the coils are later soldered to commutator segments.

ture to *reverse its direction.* Each pole of the armature will then become the same as that of the field magnet adjacent to it (see letters outside poles), and field and armature poles will *repel* for a quarter turn and attract for the next quarter turn. Then the commutator segment in contact with each brush will again change, and the entire process will be repeated, thus securing constant rotation in one direction.

236. Commercial Motors. — The motor just described would not run smoothly when loaded, because of the difference in the turning force at different points in the rotation.

To make the force between armature and field as constant as possible, a large number of coils are wound in evenly placed slots in a soft-iron armature core (Figure 372). There are as many commutator segments (Figure 373) as there are coils, and to each commutator segment is connected the beginning of one coil and the end of another. In this way the current that reaches the motor through the brushes flows through all the coils, each coil contributes its own pull, and the resulting turning force is nearly constant. The difference between such a commercial motor and the motor described in the previous section could be compared to the difference between a "twin-six" automobile engine and a single-cylinder motorcycle engine.

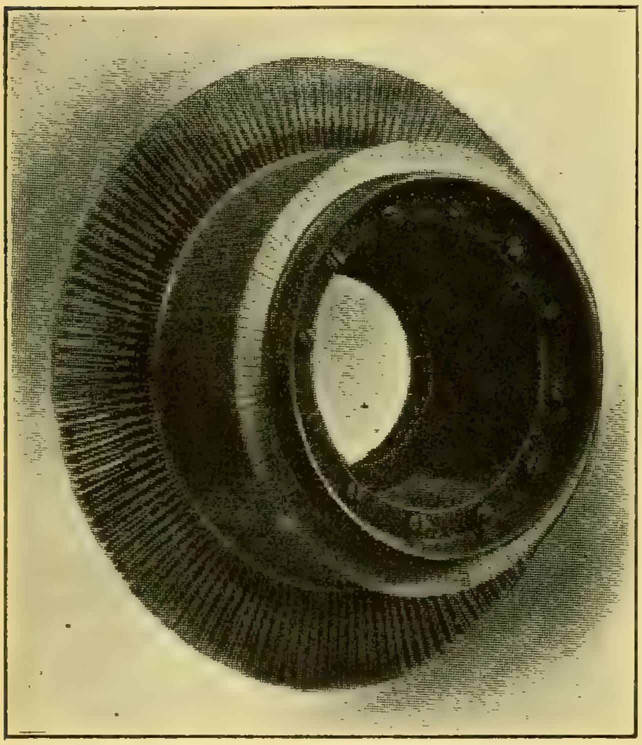


FIGURE 373. — COMMUTATOR OF LARGE MOTOR.

Each of the many commutator segments terminates at the left in a fork into which the beginning of one coil and the end of another are soldered.

The field poles of commercial motors are usually four or some other even number, so connected that they are alternately N and S. In *shunt* motors (Figure 374), the current from the line divides, the greater part passing through the relatively few turns of large wire of the armature, and a small portion going through a large number of turns of smaller wire in the field. Such motors have nearly the same speed for all loads, and are used for a greater variety of purposes than

any other direct-current motors. *Series* motors (Figure 375) have the same size wire on armature and field poles, and all the current passes through both armature and field. These motors slow down very much under heavy loads, but have the advantage of exerting great force when starting or running slowly. This makes them suitable for electric cars, electric automobiles, and hoisting machinery, where the load is attached to the motor at all times.

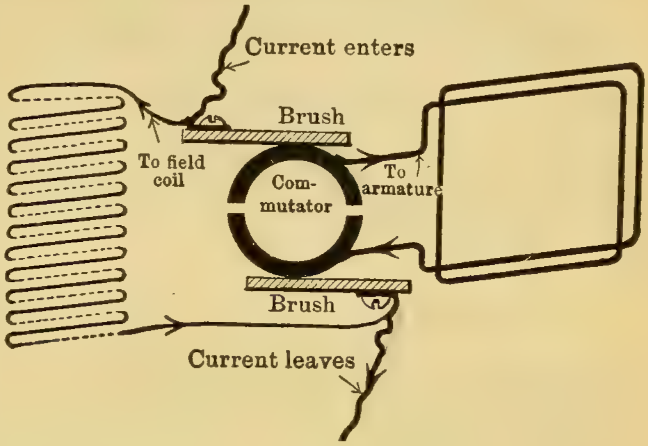


FIGURE 374. — SHUNT MOTOR, CIRCUIT DIAGRAM.

Right, armature: few turns, large wire. Left, field coil: many turns, small wire.

QUESTIONS

1. State four essential parts of an electric motor.

2. Is the current in the armature of an electric motor direct or alternating? How is this result secured?

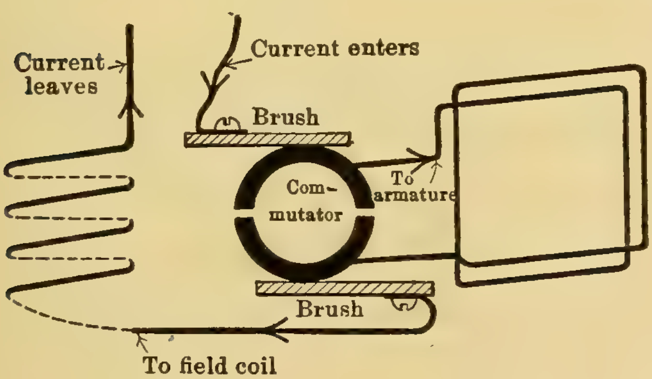


FIGURE 375. — SERIES MOTOR, CIRCUIT DIAGRAM.

Large wire in both armature and field, and entire current passes through both.

3. Why are there many coils and commutator segments in a commercial motor?

4. Compare the size of the armature and field windings in a shunt motor.

5. What is the speed variation of a shunt motor? Why is this type very widely used?

6. Describe the path of the current in a series motor.

7. What advantage has this type of motor? For what is it used?

SUMMARY

A **conductor carrying a current** is surrounded by magnetic lines of force. The **direction of these lines** is remembered by the following rule: Grasp the conductor with the right hand, so that the thumb points in the direction in which the current is flowing, then the fingers will point in the direction in which the lines of force encircle the wire.

A **solenoid** is a coil of wire. When it carries a current, it behaves like a bar electromagnet. The **strength of the magnet** depends on the number of **turns**, the **current** flowing through them, and the permeability of the **core. Permeability** is the measure of the ability of a substance to concentrate lines of magnetic force. The **polarity of the solenoid** is in accordance with the following rule: Grasp the coil with the right hand so that the fingers point in the direction of the current; the extended thumb will point in the direction of the north pole.

Horseshoe electromagnets consist of straight iron cores wound with wire and connected at one end by a yoke of permeable iron. The current passes around the two cores in opposite directions. Lifting magnets and field magnets are special forms of horseshoe magnets.

In a **circuit-breaker**, excessive current in a solenoid trips a latch, which causes the circuit to open.

Electric bells and buzzers contain electromagnets that attract a soft-iron armature; as this is attracted, the circuit is broken, and a spring closes it again, thus causing a succession of sounds.

The **telegraph key** opens and closes the main circuit. When current passes through the **sounder**, the armature is drawn forcibly down against an anvil; when the circuit is opened, a spring pulls the armature up again. **Relays** are electromagnetic switches, operated by small currents, so that they open and close local circuits containing sounders or other apparatus.

An **electric motor** consists of a stationary field electromagnet

and an armature electromagnet that is free to turn. The current is led into the armature through brushes and a commutator. The current in the armature alternates in direction, so that the poles of the armature are alternately attracted and repelled by those of the field.

Shunt motors have a small part of the line current flowing through the field. They are constant in speed and are used for most purposes. In **series motors** all the current flows through the field. They are used in electric cars.

EXERCISES

1. Show by diagram the position taken by four compass needles placed around a vertical wire carrying a current; indicate the direction in which the current is flowing.

2. Why are watches likely to become magnetized when carried near conductors in which large currents are flowing?

3. If a bar electromagnet is suspended so that it can turn freely, what position will it take?

4. Explain how you could determine the direction in which current is flowing in a wire by means of a compass needle.

5. Which will be the stronger magnet, one of 100 turns through which 2 amperes of current are flowing, or one of 20 turns through which 50 amperes of current are flowing?

6. If you had a circuit in which only a small current was available, would you use a magnet of many turns of fine wire, or one of few turns of coarse wire?

7. Illustrate the answer to the preceding question from a telegraph system.

8. State two differences between a circuit-breaker designed to allow 10 amperes of current to flow before it opens, and one designed to open at 1000 amperes.

9. State what adjustment you would make of an electric bell if it rang feebly.

10. Diagram the connections for an electric bell that may be rung from three different buttons.

11. Diagram the connections for ringing three electric bells from one button.

12. Show the wiring for a 3-drop annunciator.

13. Describe in detail the operation of an electric bell.

14. Compare a push button and a telegraph key as to (*a*) construction; (*b*) action. Diagrams required.

15. Why is a dynamo used for the main line of a telegraph system and batteries for the local circuits?

16. Make a labeled diagram of a telegraph system of two stations, with both sounders and relays.

17. By reference to the diagram, state all the steps in sending a message and replying to it.

18. Explain fully the action of an electric relay, with the aid of a diagram.

19. What is meant by a *remote-control* system? State some of its advantages.

20. Make a diagram of a simple electric motor, showing the path of the current.

21. Explain in detail how the armature of the motor is caused to rotate continuously in one direction.

22. Why do shunt motors have small wire on the field coils and series motors have coarse wire?

23. The starting motor of an automobile is a series motor. Why?

24. Give six different uses of electric motors that you have seen.

CHAPTER XIX

ELECTRICAL UNITS

The exact nature of electricity is as yet a matter of theory and conjecture. Many years of experimenting, however, have taught us that it behaves in a certain way under certain conditions. This regularity of behavior makes it possible for us to formulate laws to express its behavior and to establish *units* by which its quantities can be measured without reference to any theory concerning its nature. The increasing usefulness of electricity makes the measurement of it necessary. Electricity is bought and sold like any other commodity, so the rate at which we receive it, the pressure pushing it, and the amount of electrical energy received must all be determined.

For centuries, men believed that electricity was a kind of fluid. This fluid was supposed to move from one substance to another without detection and without change of weight in the bodies that gained or lost it. Even to-day, the behavior of electricity is so much like that of a weightless fluid, that we apply terms to it such as we would apply to a fluid. We still speak of the flow or *current* of electricity, or of electrical pressure, just as though it really were a fluid. These terms are so useful in helping to get clear ideas about electricity that we shall continue their use.

237. The Coulomb. — Even in the fluid idea of electricity, it was not considered as always moving. Electricity is sometimes stationary, or *static*. A certain quantity

of electricity at rest constitutes a *coulomb.* The coulomb measures electricity just as a quart measures water or milk. While not important in itself, the coulomb is important in aiding us to get the right idea about the measurement of the rate of flow of electricity.

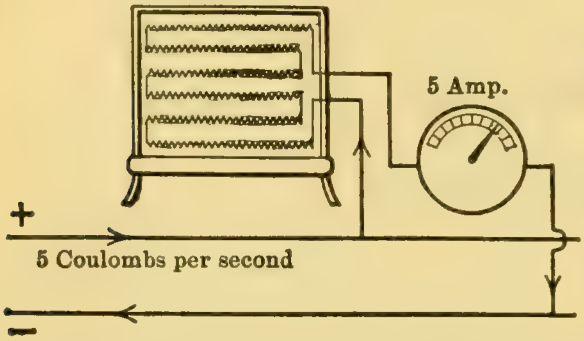


FIGURE 376. — When 5 coulombs of electricity pass through the toaster in 1 second, the current is 5 amperes.

238. The Ampere. — The unit of rate of flow is the *ampere,* named in honor of a famous French scientist. The word *ampere* means a coulomb-per-second. The coulomb, being a certain quantity of electricity, when moving through a circuit in a second, constitutes an *intensity* of current of one ampere (Figure 376). In speaking of the rate of flow of a current, the proper term to use is *intensity,* but we commonly use the simple word *current* or *current strength* to express the same idea.

In the flow of liquids (Figure 377), we have no word that means quart-per-second, hence we are obliged to use the whole phrase. In electrical systems, to express the

FIGURE 377.—TOWER FALLS, YELLOWSTONE. Five cubic feet per second of water pass over the brink of the falls.

André Marie Ampère (1775–1836) was an exceedingly versatile French mathematician, physicist, and philosopher. At the age of twelve he studied Latin so that he might read the treatises of the great mathematicians. Later when Oersted had discovered the magnetic effect of an electric current, Ampère was able to reduce this relation to a law and to express the magnitude of the effect by a formula. Much of the work of later scientists was based upon Ampère's discoveries and reasoning.

corresponding idea of coulomb-per-second, we have the single word *ampere*. Since we are much more concerned with electricity in motion than we are with electricity at rest, the word *ampere* will be commonly used, while the word *coulomb* is seen but seldom.

Incandescent lamps require less than an ampere of a current, the common sizes less than one half of an ampere (Figure 378). An electric flatiron operates on about 4 or 5

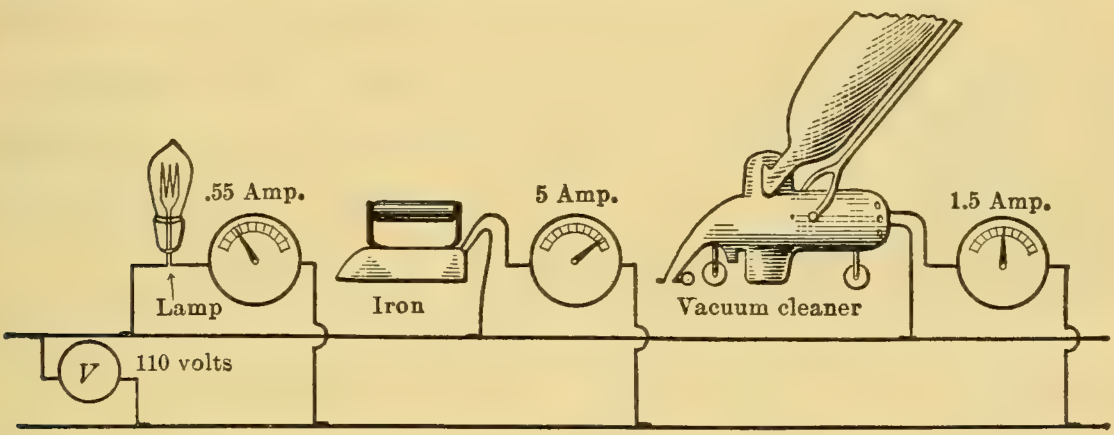


FIGURE 378. — The lamp, the iron, and the vacuum cleaner take different amounts of current from the line. The voltmeter, connected across the line, measures the pressure.

amperes. Motors take varying currents, according to the work done by the motor. Small motors for domestic use on fans, sewing machines, and vacuum cleaners operate on an ampere or thereabouts, while a street-car motor may take 50 amperes.

239. Electrical Pressure. — Whatever electricity is, it will not move unless acted upon by a force or pressure. This pressure is called **E**lectro**M**otive **F**orce, the initials E.M.F. being often used for the phrase. This electrical pressure, or E.M.F., exists between any two bodies that have a different charge. In an electric cell, one pole or plate is given a negative charge, while the other pole is given the opposite or positive charge. Chemical changes in the cell produce

these charges, while in a dynamo the same result is accomplished by the process of induction. Between these two unlike charges there is a strong tendency to neutralize, that is, to counteract each other and become uncharged again. The cell and the dynamo continuously build up the difference in charge so that a current flows as long as there is a path for it to flow through. The tendency or effort of the charges on one pole to get to the other pole is the pressure, or electromotive force, of the cell. This pressure is measurable and the unit in which it is measured is the *volt.*

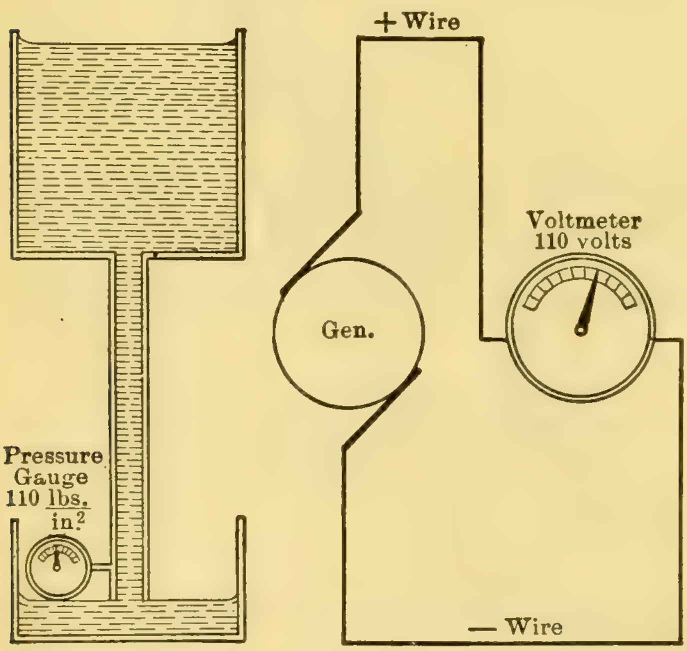


FIGURE 379. — The electrical pressure in volts corresponds to water pressure in pounds per square inch.

The volt is defined as the pressure required to push an ampere of current through a resistance of one ohm. (See § 240 for "ohm.") If the cell or dynamo has poles of different charge, a pressure may exist even though there is no conducting path through which a current can flow. In this respect, again, the electrical circuit is like a water system. The water stored in a stand-pipe or reservoir maintains a constant head or pressure that corresponds to the electromotive force or voltage of the cell (Figure 379). If a pipe is supplied to the reservoir, the pressure will cause a current to flow. If a conducting path, as a wire, is placed between the two oppositely charged poles of the cell, a current of electricity will flow. In a water system, the pressure is

usually measured in pounds per square inch; in the electrical circuit, the corresponding unit is the volt.

A new dry cell has a voltage (E.M.F.), of about 1.5 volts; most house circuits have a pressure of approximately 110 volts; long-distance transmission systems may have voltages as high as 200,000 volts.

240. Resistance. — All conductors of electricity oppose the flow of current through them. This opposition is called *resistance.* This resistance is measured by comparison with a standard and is expressed by a unit called an *ohm.* The standard, or international, ohm is the resistance of a column of mercury 1 mm^2 in cross section and 106.3 cm long, taken at 0° C. The different metals, many solutions, and some non-metals can conduct electricity, but each substance offers a different resistance to the flow of current. The resistance of any substance in turn depends upon the length, cross section, and temperature of the conducting substance used.

There is a certain opposition to the flow of water through a pipe, but there is no unit for its measurement. This resistance is largely due to the friction of the water against the pipe and is, therefore, chiefly developed when the water touches the pipe. The resistance of an electrical conductor is an effect of the material and therefore depends upon the area of the cross section. Further consideration of the laws of resistance will be given in the next chapter.

241. Ohm's Law. — For some time after current electricity was known, no one understood what determined the intensity of the current flow through a wire. It remained for Ohm to state the principle that shows the relation between current flow and the pressure applied to overcome the resistance in a circuit. Ohm's Law, which seems almost

an axiom now, marked a distinct forward step in physical science, because it did show how currents of different strength were produced. The law is stated thus: *The intensity of current in any circuit is equal to the electromotive force divided by the resistance of the circuit.*

A congress of scientists has given to the volt, the ampere, and the ohm such values that the law may be expressed by the simple relation:

$$\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}, \text{ or } I = \frac{E}{R}$$

242. The Units Distinguished. — The terms *volt* and *ampere* are frequently misused or misunderstood. This misunderstanding may be cleared up by a review of the meanings of the three units thus far considered: The *ampere* is the unit of measure of *rate* of current flow or *intensity.* The *ohm* is the unit of *resistance* or opposition to this flow of current. The *volt* is the unit of *pressure,* which drives the current through the conductor against the resistance of the conductor.

QUESTIONS

1. Why is the measurement of electrical quantities necessary?

2. In what two forms is electricity thought to exist? What is the difference between these two conditions?

3. What is a *coulomb?* Give a term applied to the measurement of a liquid that corresponds to the use of the coulomb.

4. What is an *ampere?* What two quantities are involved in an ampere? What is measured in amperes?

5. What is the current intensity in various electrical devices such as an incandescent lamp, an electric flatiron, and in a small motor? Is your answer supposed to indicate an exact amount or a reasonable amount for these devices?

6. Why does electricity move from one pole of a dry cell to the other? Will electricity move from one carbon pole of a dry cell to the carbon pole of another dry cell? Why?

7. What name is given to the cause of motion of electricity? In what units is this measured?

8. What causes water to flow through a pipe? In what units is this force measured?

9. What is the voltage of a new dry cell? Of the storage battery in some automobile that you know about? Of an incandescent lamp circuit?

10. What is electrical resistance?

11. Is resistance a property of the electricity passing through a conductor or a property of the conductor itself?

12. Name and define the unit of electrical resistance.

13. State Ohm's Law and show that it is reasonable. What equation is derived from this law?

243. Principle of Measurement of Electrical Quantities. — Electric currents produce three effects: they produce heat, magnetic fields, and chemical changes. Any one of the three can be used to detect the existence of a current in a circuit or to measure the strength of the current. In fact, each one is so used, but the effect that most measurements depend upon is the magnetic effect. A device, or instrument, that uses the magnetic field of a current to detect or compare the current with another is called a *galvanometer*. There are many kinds of galvanometers, but we shall consider only one.

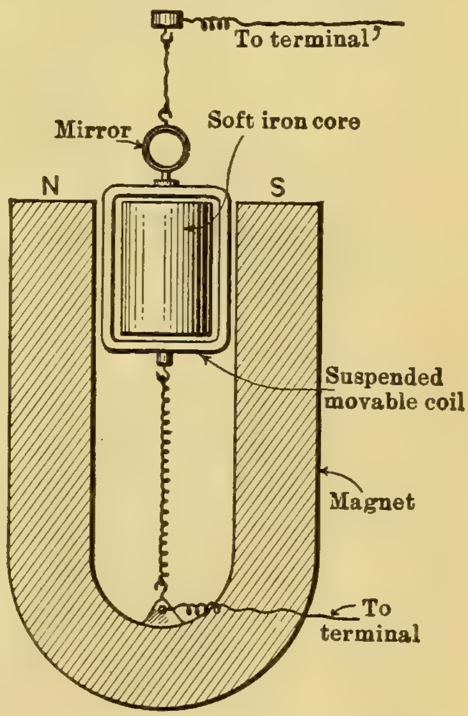


FIGURE 380. — D'ARSONVAL GALVANOMETER.

The field of the electromagnet tries to become parallel to the field of the permanent magnet. The elasticity of the suspension opposes the motion.

244. The d'Arsonval Galvanometer. — If a permanent horseshoe magnet is placed with poles up as in Figure 380, and a flat

coil of wire is suspended between the poles, the coil, when current flows in it, produces a magnetic field whose poles are in front and in back of the coil. The lines of force of the magnet try to turn the coil until the lines of force of the coil lie parallel to those of the magnet. The twisting of the suspending wire prevents a complete quarter turn of the coil and stops it at some intermediate position according to the strength of the current producing the magnetic field.

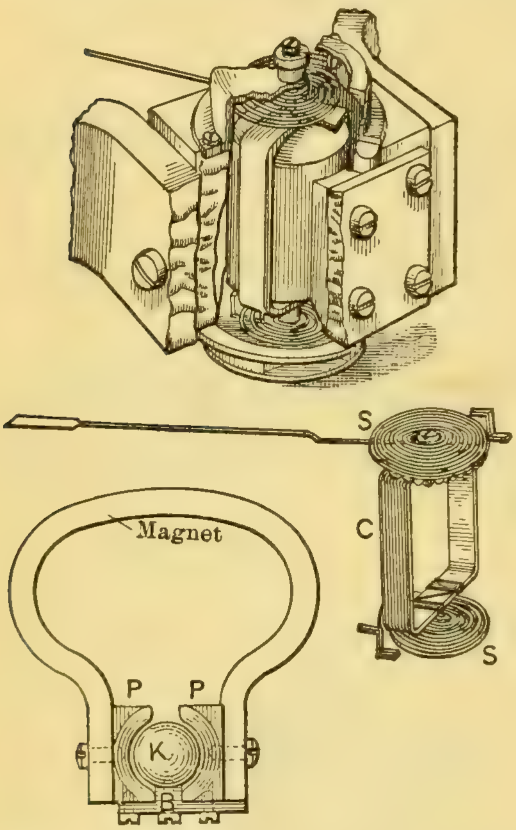


FIGURE 381. — PARTS OF A WESTON GALVANOMETER.

The top figure shows the instrument assembled, with one corner broken away. The center figure shows the moving element. The bottom shows magnet and core. *B* is a piece of brass that holds the core in place.

245. The Weston Galvanometer. — This type of instrument (Figure 381) is a modification of the d'Arsonval galvanometer. It has a coil, *C*, suspended by jeweled bearings so that it can turn freely about a stationary iron core, *K*, placed between the poles, *PP*, of a permanent magnet. The motion of the coil is limited by two hairsprings, *SS*, attached to it. The current to be indicated enters the coil by one spring and leaves by the other. If the current is weak, it makes a weak magnetic field with poles at either face of the coil. The reaction of these poles with the field poles, *PP*, moves the coil a little against the tension of the hairsprings. If the current is stronger, the field about the coil is stronger and the repulsion of the field magnet turns the coil a greater distance against

the opposition of the springs. When the current is stopped, the springs move the coil back to its neutral position. A pointer, attached to the aluminum frame that holds the coil, moves over a scale divided into convenient spaces. Since the instrument *compares* rather than *measures* currents, the spaces on the scale are used only as a means of comparison. The iron core forms a uniform magnetic field for the coil to turn through so that *the deflection of the pointer in all parts of the field shall always be proportional to the current flow.*

246. The Ammeter.— While the galvanometer is of little use outside of laboratories, it is the basis of the instruments in common use for the measurement of both current and pressure. The ammeter (Figure 382), used to measure intensity, or rate of current flow, is simply a low-resistance galvanometer, whose scale is calibrated (divided) to indicate the flow of current in amperes. The ammeter must have a low resistance, so that it will not reduce the current that it is to measure. This low resistance is obtained by the use of a *shunt*, a metal bar connecting the point where the current enters the coil with the point where the current leaves the coil. Since the resistance of this shunt is small compared to that of the coil, the greater portion of the current

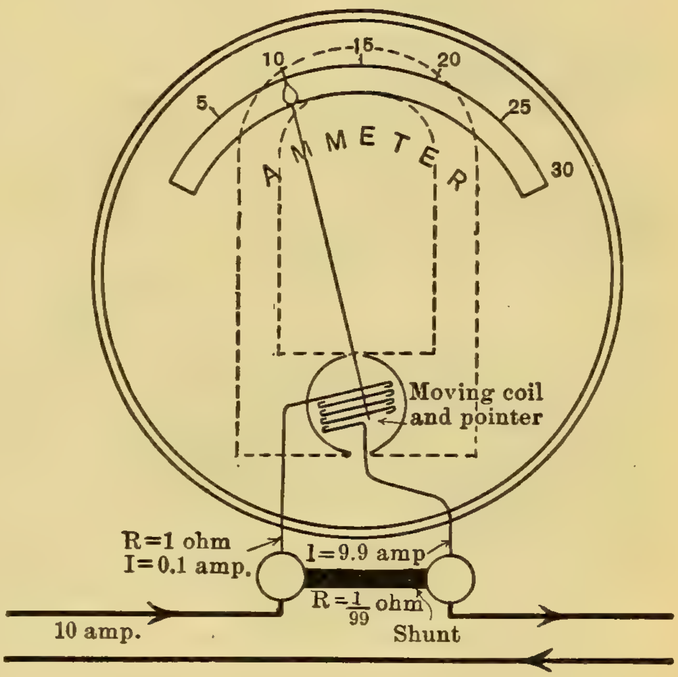
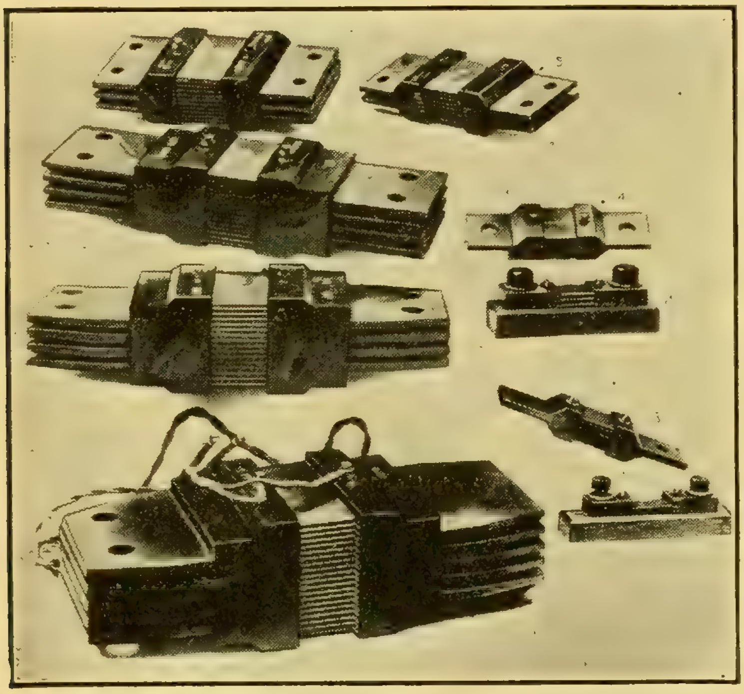


FIGURE 382. — AMMETER.

This is a Weston galvanometer provided with a shunt. In the instrument shown $\frac{1}{100}$ of the current passes through the movement and $\frac{99}{100}$ through the shunt.

passes through the shunt. On the scale, however, the numbers are made to indicate not the current actually flowing in the coil, but the total current passing through the coil and shunt. Ammeters used on circuits in which the current strength varies greatly are provided with a number of detachable shunts of different resistance (Figure 383). When a large current is to be measured, a large shunt is used. This method requires the use of several sets of figures on the scale, and the use of discretion on the part of the observer as to which set of values he shall read.



Courtesy of Weston Electrical Inst. Co.

FIGURE 383. — A GROUP OF SHUNTS.

By using large, low-resistance shunts for large currents and small, high-resistance shunts for small currents, the same ammeter may be used for a wide range of currents.

As the ammeter is to measure current intensity, it must be connected in the circuit so that all the current to be measured can flow through it. This is called a *series* connection (Figure 378). If too small a shunt is used or the instrument is connected "across the line," the low resistance permits too large a current to flow through the coil, causing the instrument to be "burned out."

247. The Voltmeter. — Ohm's Law shows that the current in a circuit is directly proportional to the electromotive force but inversely proportional to the resistance of the circuit.

In order to make use of the current strength to measure pressure, it is necessary to use a galvanometer with so high resistance that the current will depend wholly upon the pressure applied to the circuit. A voltmeter is, then, a galvanometer that has a high-resistance coil in series with the moving coil (Figure 384). Voltmeters have resistances in

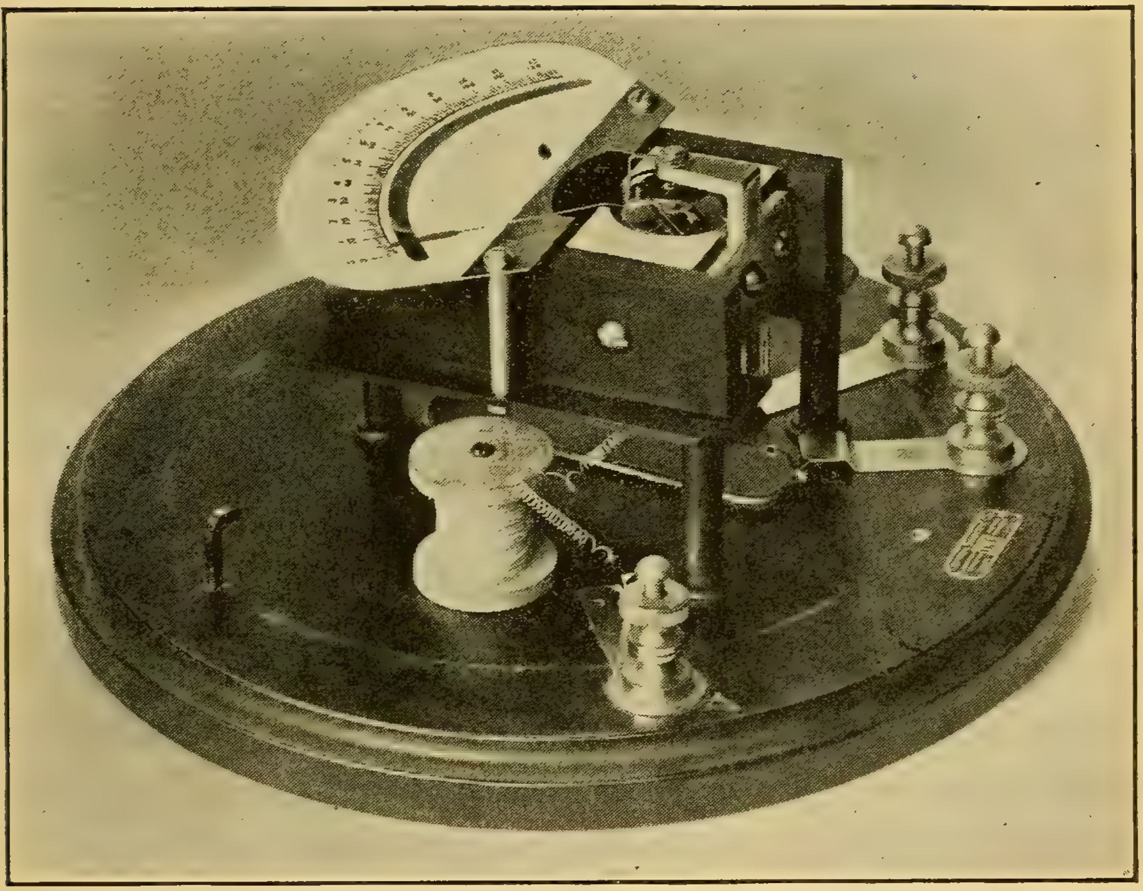


FIGURE 384. — DEMONSTRATION VOLTMETER.

The long coil of high-resistance wire beside the instrument is in series with the moving coil and reduces the current to a safe value.

the series coil of several thousand ohms. The scale is calibrated to indicate pressure in volts, since the high resistance of the series coil makes the current through the moving coil proportional to the pressure in volts.

A voltmeter, like any pressure meter, does not measure a *pressure* but rather a *difference* in pressure. The pressure at

any point of a circuit is of no importance, but the difference in pressure between that point and some other point is the effective voltage driving current from one point to the other. For example, it is of no use to know the pressure of a circuit before the current enters a lamp. It is equally useless to know the pressure after leaving the lamp. To find the pressure that is pushing the current through the lamp, we must obtain the difference in pressure between the entering point and the leaving point. To obtain this difference the voltmeter is connected across the terminals of the lamp. Then it will indicate the pressure that is sending the current through the lamp (Figure 378). This method of connecting is called *parallel*, or *shunt*, connection.

Voltmeters may be used on wide ranges of pressure if they are equipped with several independent series coils. A coil of high resistance is used when a very large pressure is to be measured and a corresponding scale must be shown on the dial of the instrument. The series coils are not expensive as compared to the remaining part of the instrument, so for a slight additional expense, the equivalent of several instruments may be obtained. For the protection of the voltmeter, a circuit of unknown pressure should be connected first to the highest range of the instrument.

248. Measurement of Resistance. — There is no direct method of measuring resistance. There are two common methods of calculating resistance. One is the voltmeter-ammeter method, the other is by the Wheatstone bridge, to be explained later.

By the former method the two instruments are connected in circuit with the resistance to be measured; the voltmeter in parallel with the resistance and the ammeter in series with

the resistance, as shown in Figure 385. The readings of the instruments are taken. According to Ohm's Law:

$$\text{amperes} = \frac{\text{volts}}{\text{ohms}}$$

$$\text{Transposing:} \quad \text{ohms} = \frac{\text{volts}}{\text{amperes}}$$

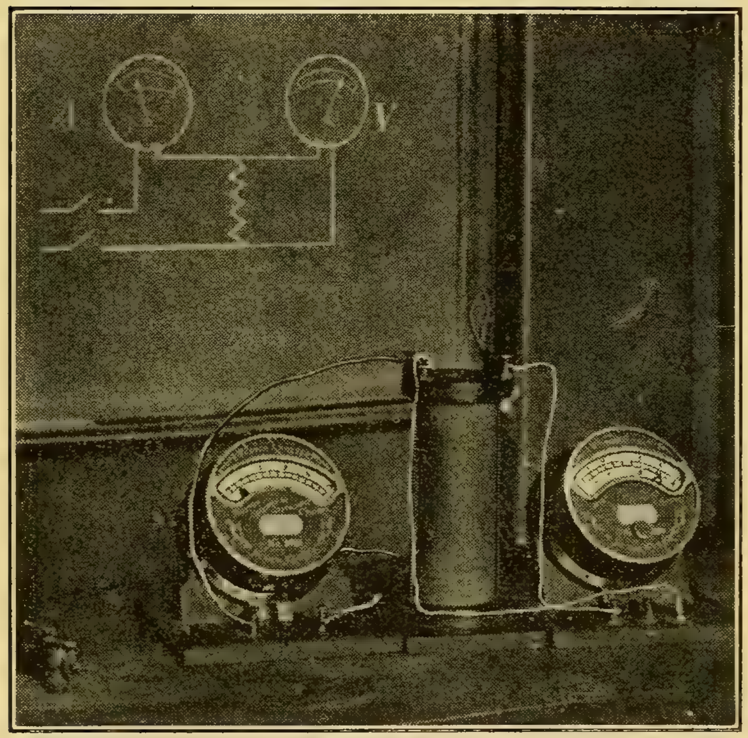


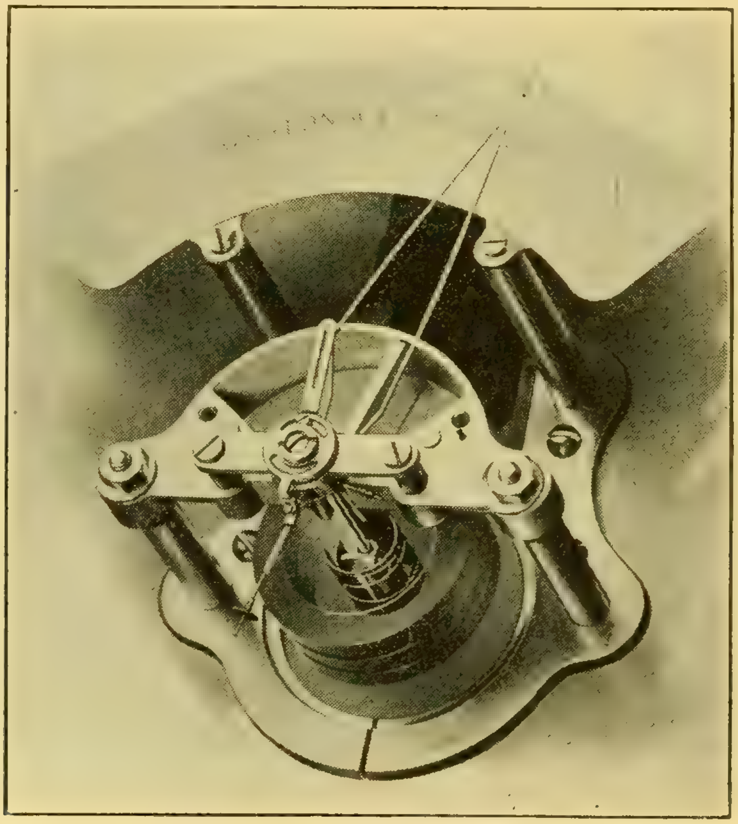
FIGURE 385. — MEASURING THE RESISTANCE OF A COIL.

The connection diagram is seen on the blackboard. Heavy wire is used for the ammeter and light wire for the voltmeter.

If the voltmeter reading is 110 volts and the ammeter reading is 5 amperes, the resistance of the toaster in Figure 376 is $\frac{110}{5} = 22$ ohms.

249. Alternating-current Instruments. — The instruments described in the preceding paragraphs can be used only in direct-current circuits (circuits in which the current flows continuously in one direction; see § 315). In alternating-current circuits (§ 312) instruments of different design are necessary. The common types of alternating-current in-

struments have a circular stationary coil, in which is a fixed and a movable piece of iron. The latter is attached to the pointer (Figure 386). The magnetic action of the current in the coil on the piece of iron causes the two pieces to repel each other. The pointer is thus moved



Courtesy Weston Electrical Inst. Co.

FIGURE 386. — SOFT IRON ALTERNATING CURRENT METER.

The current in the coil magnetizes a fixed and a movable piece of iron, shown in the center of the coil, with the same polarity. Their repulsion turns the pointer against the elasticity of a spring.

across a scale. Although this instrument can also be used on direct-current circuits, the unequal divisions on its scale make it less accurate than the ones described earlier. On the other hand, it is cheaper and less easily damaged.

Small alternating currents are measured by a hot-wire ammeter. The current to be measured passes through a wire, (PW), heats it, and causes it to sag as it expands. The

slackening of the wire permits a pointer, (N), to move across a scale and indicate the size of the current through the wire (Figure 387).

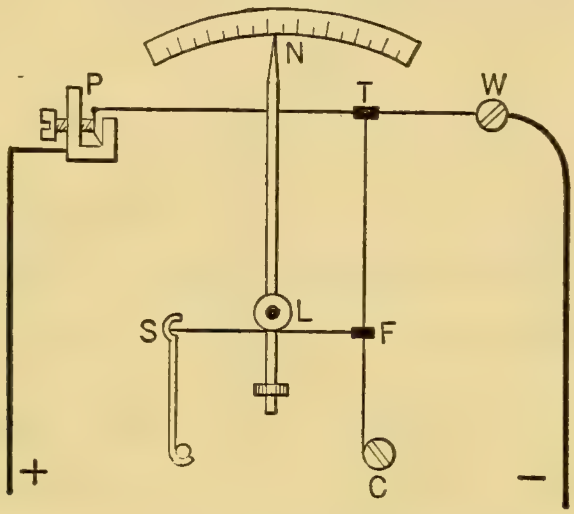


FIGURE 387. — HOT WIRE METER.

Heat produced by the current lengthens the wire *PW*, and the spring *S*, attached to the wire through *F* and *L*, causes the pointer to revolve around the pivot *L*.

QUESTIONS

1. Name three effects that may be produced by an electric current. Which of these effects is commonly used for the measurement of the current?

2. Of what parts is a d'Arsonval galvanometer constructed? How are these parts arranged?

3. What acts as an opposition to the motion of the coil in a d'Arsonval galvanometer? In a Weston galvanometer? What motion would the coil have if there were no opposition to its movement?

4. What change is necessary to convert a galvanometer into an ammeter? Why is this change necessary?

5. How is an ammeter connected in a circuit? Why?

6. Should a voltmeter have a high or a low resistance? How is the proper resistance obtained?

7. Does a voltmeter measure a pressure or a difference in pressure between two points? How should it be connected in a circuit?

8. A coil of 5 ohms resistance is connected to a battery whose E.M.F. is 6 volts. What current flows in the coil?

9. A current of 22 amperes flows in a heater coil whose resistance is 5 ohms. What E.M.F. in volts is required?

10. A voltmeter connected across the terminals of a lamp reads 110 volts, while an ammeter in series with the lamp reads 0.4 ampere. Sketch the connections and find the resistance.

SUMMARY

A **coulomb** is a unit of electrical quantity.

An **ampere** measures the rate of flow of electricity when one coulomb per second flows through a circuit. The ampere is used more than the coulomb because it *measures the flow* of electricity rather than the quantity of electricity.

A difference in charge between two bodies causes an **electrical pressure.** Electrical pressure is called **electromotive force** and is measured in units called **volts.**

All conductors offer some **resistance** to the flow of electricity. The resistance is measured in units known as the **ohm.** The value of the ohm is derived from a certain column of mercury so chosen that one volt is able to push one ampere through this resistance.

Ohm's Law states that the current flowing through a circuit, or through any part of a circuit, is directly proportional to the pressure in volts and inversely proportional to the resistance in ohms.

$$I \text{ (amperes)} = \frac{E \text{ (volts)}}{R \text{ (ohms)}}$$

Electrical currents produce three effects by which the strength of the current may be measured: they produce **heat, magnetic fields, and chemical changes.** Currents are usually measured by their magnetic effect.

A **galvanometer** is an instrument used for the detection and comparison of current. A common type of galvanometer allows the current that is to be measured to flow through a suspended coil, hung between the poles of a stationary permanent magnet.

An **ammeter** is a galvanometer of low resistance, placed directly in the circuit whose current strength is to be measured

(series). The low resistance is obtained by a *shunt* or metal bar placed across the terminals of the instrument.

The **voltmeter** is a high-resistance galvanometer connected to two points whose potential difference is to be measured. It is therefore connected in parallel. The high resistance of the voltmeter is obtained by the use of a **series coil** in the same circuit as the moving coil.

Resistance is measured by various methods of comparison or calculation. A simple means is to measure the current through the circuit and measure the difference in potential of the two ends of the circuit. The voltmeter reading divided by the ammeter reading gives the resistance (Ohm's Law).

EXERCISES

1. If you use a d'Arsonval galvanometer to compare two currents, where would you connect each pair of current leads in turn? Explain enough of the operation of the instrument to make clear how you would determine which of the currents is the larger.

2. A current of 0.5 ampere flows through an incandescent lamp under a pressure of 110 volts. What becomes of the pressure and of the current when the lamp is turned off?

3. What current flows through a bell whose resistance is 4 ohms, when the bell is connected to a 3-volt battery by a wire having a resistance of 1 ohm?

4. A storage battery has a pressure of 6 volts. What current will it send through a motor whose resistance is 0.12 ohm?

5. The resistance of a dry cell is 0.05 ohm. The voltage of the cell is 1.5 volts. What current will flow in a wire of negligible resistance connecting the terminals?

6. If the terminals in the preceding question are connected by a wire whose resistance is 0.45 ohm, what current will now flow in the connecting wire? If the wire had a resistance of 14.95 ohms, what would be the current flow in it?

7. Three coils whose terminals are AB, CD, and EF, respectively, and whose resistances are 5, 8, and 12 ohms, are connected B to C, D to E, and A and F to a dynamo. Find the reading of a voltmeter connected to the terminals of each coil, and also to A and F, if a current of 2 amperes flows through the coils. (Diagram required.)

8. An electric flatiron, connected to a circuit whose pressure is 108 volts, lets 4.5 amperes flow through the coil of the iron. What is the resistance of the iron?

9. The current through the motor of an electric washer is 4 amperes when the motor is starting. If the pressure is 110 volts, what resistance does the motor have?

10. An arc lamp should have a current of 25 amperes to light properly. Its resistance is only 1.6 ohms. What additional resistance should be put in series with the lamp, if the lamp is to be used on a 110-volt circuit?

11. A bell has a resistance of 2.5 ohms. What must be the voltage of a battery to send a current of 1.2 amperes through the bell?

12. The internal resistance of a dry cell is 0.05 ohm. What must be the resistance of a wire connecting the terminals of the cell when 2.4 amperes flow through the wire, the voltage of the cell being 1.5 volts?

13. A 60-watt tungsten lamp operates on a current of 0.53 ampere on a 112-volt pressure. What is the resistance of the filament of the lamp? At the same pressure, what current would flow through a lamp of 300 ohms resistance?

14. In a street car, 5 lamps in series having a combined resistance of 1375 ohms are lighted by a current of 0.4 ampere. What must be the voltage of the street car circuit?

15. Boys sometimes try to operate a bell or magnet on a 110-volt house circuit. How much additional resistance must be put with a 3-ohm bell so that the 10-ampere fuses of the circuit will not be blown?

16. A current of 4 amperes flows through the heater coil of a street car. What is the resistance of the coil if the pressure is 524 volts?

17. Find the current flow in a percolator connected to a circuit of 120 volts pressure, if the resistance of the coil is 15 ohms.

18. A voltmeter may have several scales, so that by changing the connection the index may show 150 volts, 50 volts, or 5 volts by the same deflection of the index. Explain why this is possible and why it is desirable.

19. Shunts on an ammeter are usually detachable, so that any one of two or three different shunts may be used on the same instrument. Explain how these shunts would be used to measure current of widely different values. How should the scale of such an instrument be marked?

20. The moving coil of an ammeter has a resistance of 1 ohm, and the shunt has a resistance of $\frac{1}{200}$ ohm. How does the current divide between the coil and the shunt? Does the index show the current through the coil or through both?

21. A careless student connects the ammeter mentioned above, *in parallel* with a lamp on a 110-volt circuit. What current will flow through the instrument and what effect will this current have upon the instrument?

22. A voltmeter is connected to the two brushes of a generator. What will the reading of the instrument show?

23. What will a voltmeter indicate when it is connected across the terminals of a lighted lamp?

24. Name two methods of measuring resistance. Make a sketch diagram of connection to show that you understand one of these methods. Assume values for the necessary readings, and calculate the resistance of a coil.

CHAPTER XX

ELECTRICAL MEASUREMENTS

250. The Electric Circuit. — Before taking up electrical measurements, we may profitably examine a simple electrical circuit, such as that of the electric bell (Figure 388). We find a battery of dry cells furnishing the pressure or *volts* necessary to force the *amperes* of current through the wires that connect the door with the bell and through the magnets of the bell itself. A push-button or switch leaves a gap in the conducting circuit until the caller closes it, thus establishing a complete conducting path through which the current may flow. Wires, bell, and battery all have resistance measured in *ohms*, opposing the flow of the current. In the preceding chapter, the relation between these three fundamental quantities has been stated as Ohm's Law:

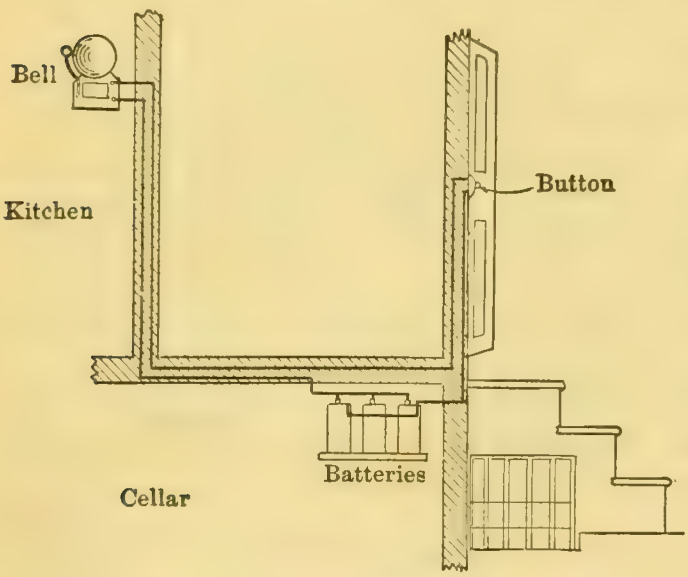


FIGURE 388. — AN ELECTRIC BELL CIRCUIT.

The battery furnishes the volts that force the amperes to ring the bell when the button is pushed.

The current in the circuit

$$= \frac{\textbf{the electromotive force of the battery}}{\textbf{the resistance of the circuit}}$$

$$\textbf{amperes} = \frac{\textbf{volts}}{\textbf{ohms}} \qquad I = \frac{E}{R}$$

If we connect a voltmeter across the terminals of the battery it will measure the pressure applied to the circuit. An ammeter connected in one of the line wires, so that all the current will flow through it, will give us the current. Substituting the values obtained from the instruments in the equation for Ohm's Law given above, the resistance of the entire circuit may be calculated.

The electrician who installs the bell, however, must know beforehand its resistance and that of the wires, in order to know how many cells will be necessary to produce the pressure needed to send the proper current through the bell. It is of the utmost importance, therefore, for all practical electrical workers to be able both to calculate and to measure resistance accurately.

251. Factors of Resistance. — It has already been stated (§ 240) that the resistance of any conductor depends upon its length, the area of its cross section, its material, and its temperature. Let us find a relation between the resistance and each of these quantities.

252. Length and Resistance. —

Experiment 100. — Cut off a piece of insulated copper wire # 28, a little over 4 meters long. Scrape the insulation off the ends, and connect them to the two outer binding posts, A and B, Figure 389, so that there shall be exactly 4 meters of wire between the binding posts. Find the exact center of the wire, scrape off the insulation, and clamp in it the center binding post C. Connect a dry cell to the two outer binding posts, so that the current shall be sent through the entire 4 meters of wire. Connect the terminals of a voltmeter to one end binding post and to the center binding post. Record the voltage required to send the current through the 2 meters of wire. Then connect the voltmeter to the two outside

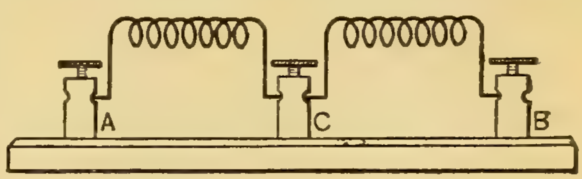


Figure 389. — Resistance Frame. Double Fahnstock binding posts are convenient.

terminals, and record the voltage required to send *the same current* through the 4 meters of wire. *How does the voltage required for 4 meters compare with the voltage for 2 meters?*

Since the same current flows through the entire wire, the reason that twice as many volts are required to send the current through 4 meters as through 2 meters shows that the resistance of 4 meters is twice as great as that of 2 meters. This result is what we might have expected and is evidence of the Law of Length:

The resistance of a conductor is directly proportional to its length.

253. Area and Resistance. —

EXPERIMENT 101. — Using the same binding posts as in the previous experiment, connect 2 meters of #28 copper wire between one end post and the center one and 2 meters of #22 copper wire between the center post and the other end post. The diameter of #22 is twice that of #28. *What is the ratio between their areas?* Connect the dry cell to the outer posts; read and record the readings of the voltmeter when it is connected across the ends of each of the wires. *Which wire requires more voltage to send the current through it? Which wire has the greater resistance? How many times is its resistance as great as that of the other? Form a proportion with areas on one side and resistances on the other, correctly arranged.*

We again have the same current flowing through both the large wire and the small one, and find that four times the pressure is required to send the current through the wire that has $\frac{1}{4}$ the area of cross section. For the # 22 wire A is large and R is small; for the # 28 wire A is small and R is large (Figure 390). The areas of the wires are as 4 to 1: their resistances are as 1 : 4. Since to make an equality of the two ratios, we must invert one of them, we find that *the resistance of a conductor is inversely proportional to its area of cross section.* The areas of two similar conductors are proportional to the squares of their diameters. Hence the re-

sistances of two wires are inversely proportional to their diameters squared. This seems the more reasonable when we consider that a # 22 wire would furnish a current path that would be equivalent to four # 28 wires placed side by side; hence four times as much current would be forced through the # 22 wire by the same pressure. According to Ohm's Law, this would mean that the resistance is one fourth as much.

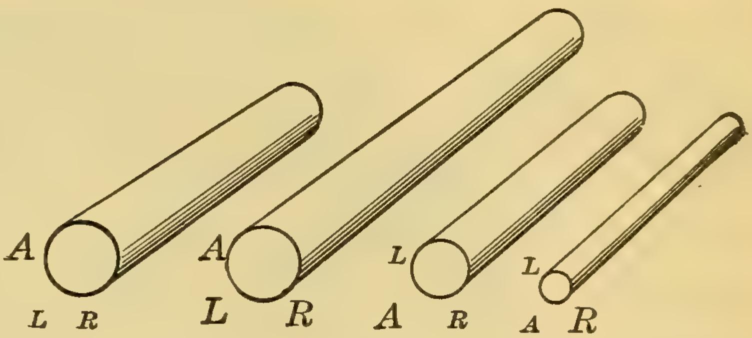


FIGURE 390. — A large wire has less resistance than a small wire of the same length; a long wire has more resistance than a short wire of the same diameter.

254. Material and Resistance. —

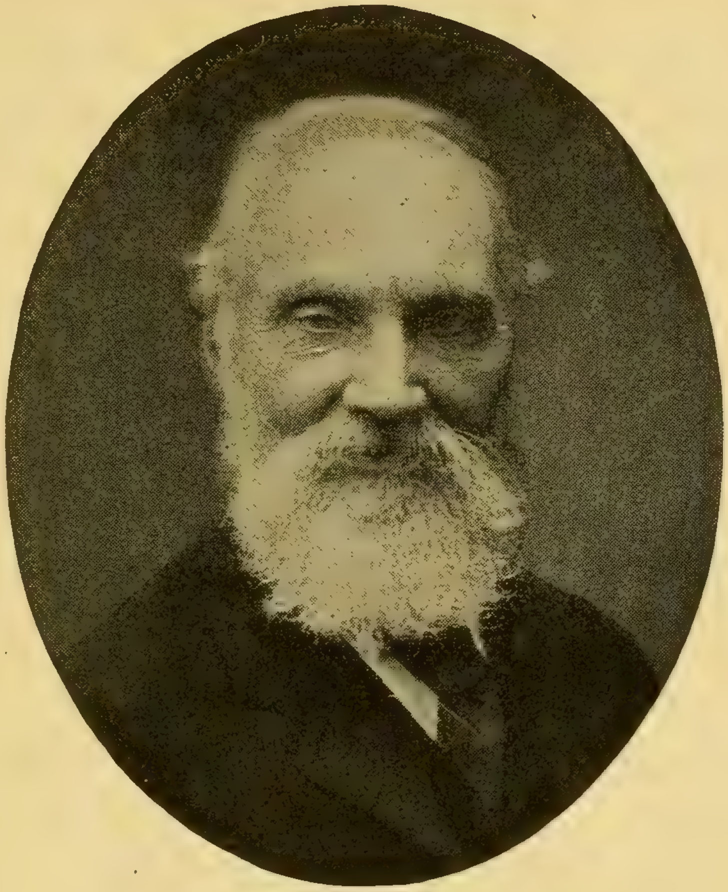
EXPERIMENT 102. — Using the same apparatus as in the previous experiments, place in series a piece of copper wire and a piece of iron wire of the same length and cross-section area. Record the reading of the voltmeter when it is connected across the ends of each wire. *Which requires the greater voltage? Which has the higher resistance?*

There is a wide difference between the resistance of conductors having the same length and cross section, but made of different materials. The reason that copper is more universally used than any other metal for electrical work is that its *specific resistance* is less than that of any other metal except silver. By specific resistance we mean the resistance of a piece of unit length and cross section. Next to copper in low resistance comes aluminum. This metal is so much lighter than copper that for wires of the same length and weight, the aluminum wire will have less resistance, because its area of cross section is so much greater. For this reason, aluminum is largely used in power-transmission lines, because

for the same current-carrying capacity, the aluminum line is lighter than the copper wire. Iron, German silver, and many special alloys are high-resistance materials, and are therefore adapted for use in resistance coils, rheostats, and heating units, where it is desirable to secure considerable amounts of resistance in a limited space. The high resistance and low melting point of lead and its alloys makes them peculiarly suitable for fuses (§ 275).

Carbon is the only non-metallic solid whose resistance is low enough to make it of practical use as a conductor. Materials of exceedingly high resistance, such as glass, porcelain, hard rubber, and Bakelite, are called *insulators*. The difference in conducting power of different materials is probably due to the number of free electrons that they contain, since the passage of the current is really the movement of these electrons. The metals are believed to contain a large number of free electrons. It will be noticed that the best conductors of electricity, the metals, are also the best conductors of heat, and that the rank of the different metals in conducting power for heat and electricity is usually the same.

255. Resistance Calculations for Wires. — If we adopt a convenient length and area for our standards of specific resistance, we can easily calculate the resistance of wires or other conductors. Electrical engineers use the *foot* as the unit of length and the *circular mil* as the unit of area. A wire with these dimensions is called a *mil-foot.* The circular mil needs some explanation. A *mil* is one thousandth of an inch (0.001 in). A *circular mil* is the area of a circle one mil in diameter. The circular mil area of any wire will be the *square* of its diameter in mils. For example, # 14 wire, used for house wiring, has a diameter of 0.064 in, or 64 mils. It has, then, a circular mil area of $64^2 = 4096$ C.M.



Lord Kelvin (William Thomson, 1824–1907) was professor of natural philosophy at Glasgow for over fifty years and profoundly influenced the scientific thought of the time through the men who came to work under his instruction. It is difficult to associate the name of Kelvin with any one definite physical idea. He connected the ideas of heat and energy which had been advanced by Rumford, Davy, Mayer, and Joule, and added to the principle of conservation of energy the idea of the dissipation of energy. His improvements made ocean telegraphy possible. He devised accurate instruments for the measurement of every electrical quantity. There is no field in theoretical physics whose boundaries were not extended by Kelvin's contributions, and in many fields he made practical appliances of great value.

When the specific resistance (k), in ohms per mil-foot, has been carefully determined for a metal, it is easy to calculate the resistance of a round wire of that metal by multiplying the specific resistance by the length (l) of the wire in feet and dividing by the area (C.M.) of the wire in circular mils. In formula form:

$$R = \frac{kl}{C.M.}$$

The value of k in ohms for a few important conductors is given in the following table:

Copper	10.4	German silver (18%)	180	Climax	480
Aluminum	17.5	Manganin	270	Nichrome	660
Platinum	72	Advance	294	Tungsten	600
Iron, pure	61	IaIa, hard	300		

256. Temperature and Resistance. — Since the temperature of a conductor may be changed by the weather or by heat developed within the wire itself, the temperature must be taken into account in calculating the resistance. With pure metals and most alloys, the resistance increases when the temperature rises; in carbon and electrolytes, heating reduces the resistance. The amount of change varies with different conductors, but for pure metals the increase in resistance is not far from 0.4% for 1° C, which means 4% for 10° C. This change makes the proper cooling of electrical machinery important.

The change in resistance with the temperature is generally less for alloys than for pure metals. By careful experimenting, alloys have been made in which the change per degree is less than one part in a million. *Manganin,* composed of 84% copper, 12% nickel, and 4% manganese, is such an alloy and *constantin* is another. These alloys with a zero-temperature coefficient are particularly useful in the moving

coils, resistances, and shunts of electrical measuring instruments and in resistance boxes.

QUESTIONS

1. What causes the flow of an electric current and what opposes the flow? Name the unit in which each of these is measured.

2. What is one method of measuring the resistance of an electrical circuit? What quantities must be determined? How are the quantities used in calculating resistance?

3. State Ohm's Law in words, in units, and as a formula.

4. Upon what four factors does the resistance of a conductor depend?

5. What is the law stating the relation between the length and the resistance of a conductor? If 1000 feet of No. 10 copper wire has a resistance of 1 ohm, what is the resistance of a mile of the same wire?

6. If lengths are equal and material the same, how does the resistance of thick wire compare with that of thin wire? How does the carrying power of wires vary with their diameters? Is this true of water pipes?

7. The resistance of 100 feet of bell wire is 0.63 ohm. What is the resistance of 200 feet? Of 700 feet? Of 25 feet?

8. How many feet of the same wire will have a resistance of 1 ohm?

9. The resistance of a wire is 25 ohms. What would be the resistance of a wire of the same length, having 5 times the cross-section area?

10. Two pieces of copper wire have the same length, but one is 3 times the diameter of the other. Which has the greater resistance? How many times is its resistance as great as that of the other?

11. A cable is made of 7 pieces of wire of the same size and length twisted together. The resistance of one of these pieces is 42 ohms. What is the resistance of the cable?

12. What causes wires of the same length and diameter to have different resistances? Give examples of this variation, beginning with a wire of high resistance.

13. Why is copper wire so largely used? Why is aluminum also widely used?

14. Name three conducting materials in the decreasing order of their specific resistance.

15. Define *specific resistance; mil; mil-foot.* State the equation for calculating the resistance of a conductor, giving the meaning of each symbol.

16. Express the following diameters in mils: 0.1 in; 0.064 in; 0.025 in; 0.005 in; 0.46 in. Calculate the area of each of these wires in circular mils.

17. A magnet is wound with 400 feet of copper wire, the diameter of which is 0.012 inch. Find the resistance of the magnet.

18. A transmission line is made of aluminum wire 1 inch in diameter. What is the resistance of 20 miles of this wire?

19. What effect have temperature increases upon the resistance of pure metals? Upon non-metallic conductors?

20. Name an alloy whose resistance is not affected by temperature changes. Where would such a conductor be useful?

257. Series and Parallel Circuits. — The electric-bell circuit described at the beginning of the chapter is a typical example of a *series* circuit. The − terminal of each part of the circuit is joined to the + terminal of the next part, so that all of the current flows through each part of the circuit. The *total resistance* of this single path, therefore, will be the *sum* of the resistances of its parts.

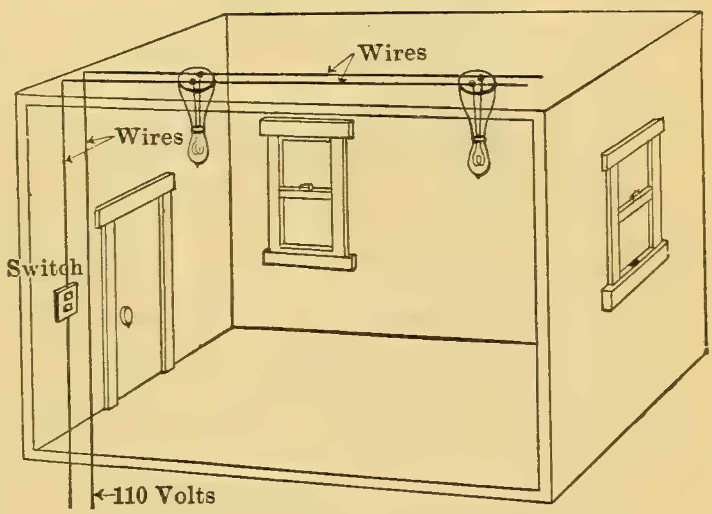


FIGURE 391. — LAMP CIRCUIT.

The wall switch admits current to both lamps. All the current flows to the first lamp. Part of the current lights this and the remainder goes on to the second lamp. The entire current returns to the main from the first lamp.

The lamps in a room are connected *in parallel;* we often turn them all on with one push switch. A simplified diagram of their connection is shown in Figure 391. It will be seen there that the current divides at the first lamp,

part of it going through that lamp and part going on to light the other. If the main switch is closed, either of the lamps may be turned on or off at will by its own key, without affecting the current in the other lamp. The more lamps that are lighted, the more current flows through the main wires. Since the voltage supplied to the room is kept constant, it is evident that by *increasing the number of paths* (lamps), for the current, we have *decreased the resistance* of the circuit as a whole. This is because the filaments of the lamps, taken as a whole, constitute a conductor whose cross section is as many times as great as that of one lamp as there are lamps. With *equal* resistances in parallel, then, the combined resistance is equal to one of the resistances *divided* by the number of resistances. Thus if 10 lamps of 220 ohms each are connected in parallel, the combined resistance will be $\frac{220}{10} = 22$ ohms.

258. Unequal Resistances in Parallel. — When the parallel resistances are not equal, the combined resistance must be found in another way. From Ohm's Law it follows that the greater the resistance in a wire, the less its current-carrying power, or *conductance.* The conductance of a conductor may be numerically expressed by taking the reciprocal of the resistance $\frac{1}{R}$ and expressing it in *mhos* (*mho* is ohm spelled backward). Thus, if the resistance of a lamp is 220 ohms, its conductance is $\frac{1}{220}$ mho. *The combined conductance of the lamps in a circuit is the sum of the conductances of the lamps.* Thus, if the resistance of one lamp is 220 ohms, another is 440 ohms, and a third is 110 ohms, the respective conductances will be $\frac{1}{220}$ mho, $\frac{1}{440}$ mho, and $\frac{1}{110}$ mho; their combined conductance will be the sum of these,

$\frac{2+1+4}{440} = \frac{7}{440}$ mho. But $\frac{7}{440}$ mho conductance corresponds to $\frac{440}{7} = 62.86^+$ ohms. A general statement of this method may be obtained by letting R stand for the combined resistance, and $r', r'', r''', \ldots$ stand for the individual resistances of the parts of the parallel circuit. Then

$$\frac{1}{R} = \frac{1}{r'} + \frac{1}{r''} + \frac{1}{r'''} + \cdots$$

As a partial check on the accuracy of determining the resistance of parallel conductors, it may be noted that the combined resistance of any number of parallel conductors is less than the smallest individual resistance. If wires of 3, 5, and 8 ohms are placed in parallel with a 2-ohm wire, the additional wires increase the carrying power of the circuit, that is, they decrease the resistance of the circuit to less than 2 ohms.

In series circuits, add resistances; in parallel circuits, add conductances, and invert the sum to obtain total resistance.

259. Current in Divided Circuits. — Parallel circuits are often called divided circuits and sometimes multiple circuits. When the resistances are equal, the same current will flow through each; this current will be the total current divided by the number of resistances. When there are two parallel paths, each is spoken of as a *shunt* to the other. Thus, in the ammeter (§ 246), we have called the low resistance connecting the terminals a shunt to the movement. If the movement has a resistance of 1 ohm and the shunt has a resistance of $\frac{1}{99}$ ohm (Figure 392), then the conductance of the shunt is 99 times as great as that of the movement and 99 parts of the current will pass through the shunt and 1 part through the movement. There are

100 parts in all; $\frac{1}{100}$ of the current passes through the movement and $\frac{99}{100}$ through the shunt. In the path where R is large, I is small, and in the other path where R is small, I is large. Briefly stated, *the currents through the branches of a divided circuit are inversely proportional to the resistances of the branches.*

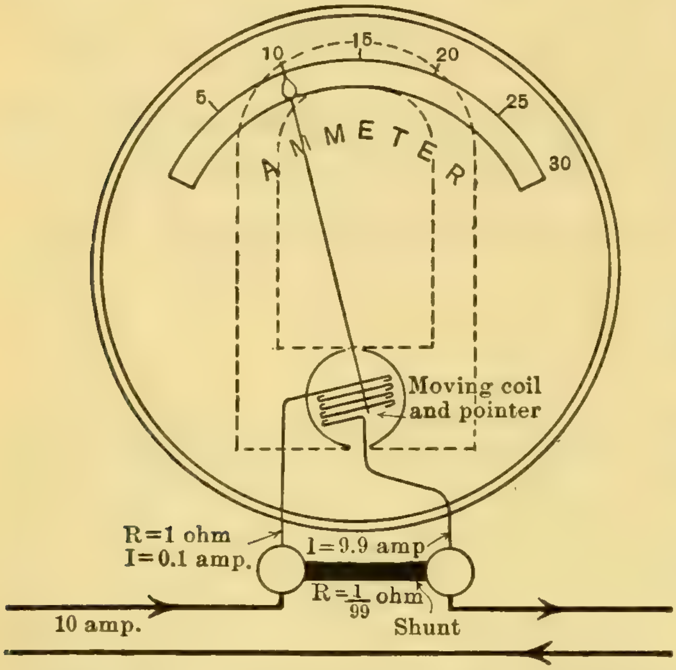


FIGURE 392. — RESISTANCES AND CURRENTS IN AN AMMETER.

$$\frac{I}{I'} = \frac{R'}{R}.$$

When the circuit has a number of branches, use of the method of conductances simplifies the calculation (Figure 393). Resistances of 2, 3, and 4 ohms are connected in parallel. What part of the current flows through each? The individual conductances are $\frac{1}{2}$, $\frac{1}{3}$, and $\frac{1}{4}$, respectively. The combined conductance is

$$\frac{6+4+3}{12}.$$

The numbers in the numerator stand for the *relative* conductance, that is, the parts of the current passing through each branch. Their sum, $6+4+3=13$, stands for the total current in the circuit. The current in the 2-ohm branch will be $\frac{6}{13}$ of the total current; that in the 3-ohm branch,

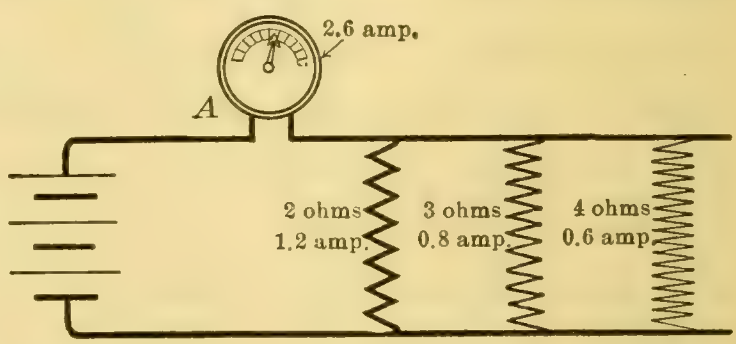


FIGURE 393. — CURRENT IN A DIVIDED CIRCUIT. Compare figures given with proportions in text.

$\frac{4}{13}$; and in the 4-ohm branch, $\frac{3}{13}$. By this method the fraction of the total current in each branch may be found, no matter how great the number of conductors in parallel. If the voltage applied to the circuit is given, the combined resistance of the circuit may be found by the method given in § 258, and the total current will be the voltage divided by the combined resistance.

QUESTIONS

1. Make a diagram of seven Christmas tree lamps connected in series to a 110-volt line.

2. As lamps are added in series, is the length or the cross section of the circuit increased? What effect does this have on the resistance?

3. An electric bell whose resistance is 5 ohms is rung by a battery whose internal resistance is 0.8 ohm. If the wires have a resistance of 0.4 ohm, what is the total resistance of the circuit?

4. A telegraph line contains ten 300-ohm relays, connected in series by wires, the total resistance of which is 13 ohms. What is the total resistance of the line?

5. Make a diagram of five lamps connected in parallel to a 110-volt line.

6. As lamps are added to this circuit, is the length or the cross-section area of the circuit increased? What effect does this have on the resistance?

7. What is the resistance of two 220-ohm lamps connected in series? In parallel?

8. What is the resistance of ten such lamps in parallel? Of 1000?

9. How does the increase in the number of lamps connected in parallel affect the lighting of the other lamps in the circuit? Is this true of a series connection?

10. How is the *conductance* of a wire of known resistance determined? What is the conductance of a 220-ohm lamp? Of a 5-ohm bell? Of a 20-ohm magnet?

11. A 3-ohm, an 8-ohm, and a 6-ohm wire are joined in parallel. What is the conductance of each of the wires? Of all three combined?

12. How is the combined resistance determined when the combined conductance is known? What is the combined resistance of the three wires mentioned in the previous problem?

13. Six lamps, each having a resistance of 90 ohms, are connected in parallel. What is their combined resistance?

14. If the lamps in Question 13 are connected to a 120-volt circuit, what is the current in each case if the lamps are turned on one by one?

15. Resistances of 8, 6, and 3 ohms are connected in parallel. What is the combined resistance?

16. A resistance of 2 ohms is shunted across a resistance of 20 ohms. What is the resistance of the circuit thus formed?

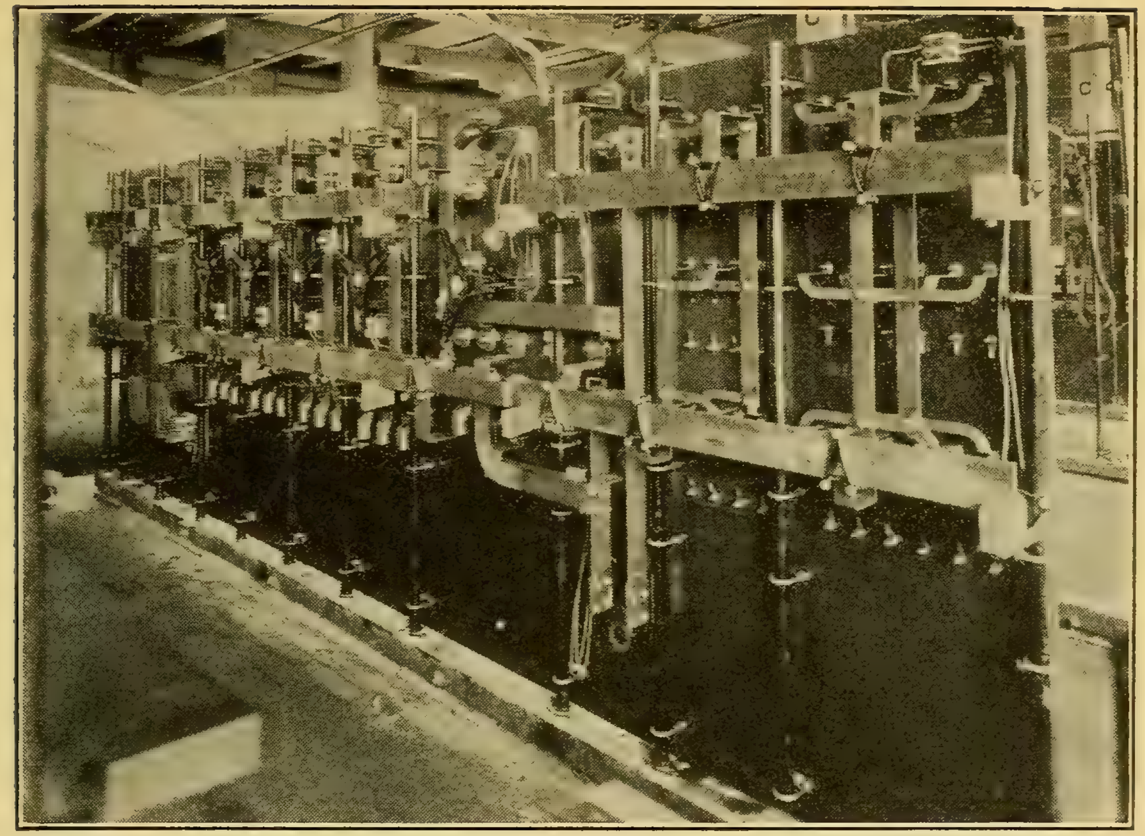
17. How does the current divide among a number of parallel paths? If 10 amperes flow through two parallel resistances of 2 ohms and 3 ohms, respectively, how will the current divide between the two branches?

18. If 33 amperes flow through the combined circuit in Question 16, how much flows through each wire?

19. Resistances of 4, 5, and 6 ohms respectively are connected in parallel. The current through the circuit is 12.33 amperes. How much flows through each wire?

260. Transmission Lines. — The facts we have learned concerning resistance and current in various circuits find their application in distributing electric current. It would be both expensive and inconvenient to have a separate dynamo for each house or building, unless the amount of power consumption is large or the building is very much isolated. So electricity is usually distributed from central stations, such as the power plant of a city, electric railroad, factory, or large building.

In a central station, the different generators are all connected in parallel to heavy bars of copper, called "bus bars" (Figure 394). From these bus bars the main distribution circuits, connected in parallel, carry the current to smaller switchboards, where the circuits again branch in parallel (Figure 395). The reason for the changes in size of wires is that in a parallel system the parts nearest the generator carry large quantities of current, a portion of which



Courtesy of General Electric Co.

FIGURE 394. — BUS BARS ON THE BACK OF A SWITCHBOARD.

The heavy horizontal bars of copper are the bus bars, and the different circuits are connected to the lighter vertical bars.

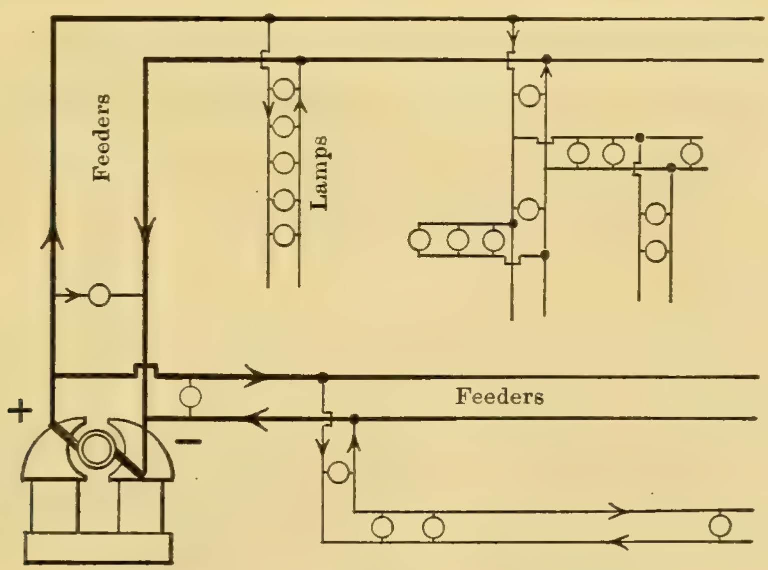


FIGURE 395. — DISTRIBUTION SYSTEM.

The feeders are in parallel, and so are the circuits taken from them. There is a switch box with fuses at each junction point. Notice the decrease in the size of the feeders as the current becomes less.

flows away in each parallel branch. Trolley wires and third rails are always large compared to house wires. Large wires must be used for large currents because the carrying power of the wire varies directly as the area of cross section.

The fact that the resistance of the line is proportional to the length limits the distance over which electric current can be economically sent from a central station. This difficulty and the tremendous cost of large conductors for heavy currents is practically met by the use of alternating-current systems. Here the current is generated at high voltage, with a corresponding reduction in the number of amperes per kilowatt (§ 263). A further reduction in the number of amperes is made by increasing the voltage for transmission by the use of step-up transformers (§ 326). These smaller currents can be carried by relatively small and inexpensive wires without at the same time causing undue loss in energy during transmission.

261. Fall of Potential. — The lights in a trolley car or electric train frequently grow dim when the car is starting; and when the car is at a considerable distance from the power house, the lights are often dim even when the car has gained full speed. The change in voltage shown by the dimming of the lamps can be investigated by a simple experiment.

Experiment 103. — Connect three or more 100-watt carbon lamps in parallel, using between each lamp and the next 10-foot lengths of #18 nichrome or other high-resistance wire, coiled as tightly as is possible without contact between the turns (Figure 396). Apply 110 volts and observe the brightness of the several lamps. Turn off the lamps, beginning with the one nearest the current supply, and observe the effect on the brightness of the last lamp.

The dimming of the lamps is due to the fact that some of the voltage available at the first lamp is used in pushing the

current through the high-resistance connecting wires to the succeeding lamps. This loss of voltage, caused by sending current through the line, is an example of *fall of potential*, and is commonly called "line drop." The lamp farthest from the current supply is brighter when the others are not burning, because, as each lamp in front of it is turned off,

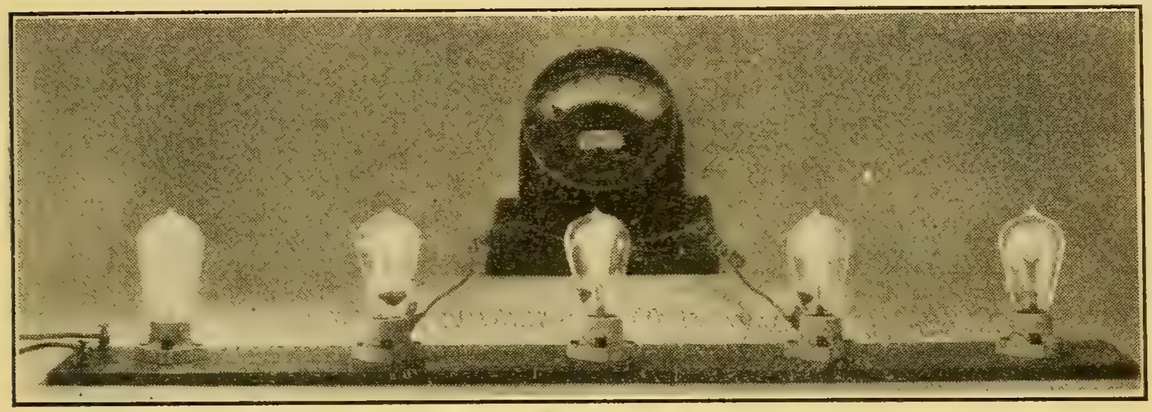


FIGURE 396. — FALL OF POTENTIAL.

The lamp connected in parallel with high-resistance wire. Note the decrease in brightness toward the right. The voltmeter is measuring the fall of potential along one side of the line between the second and fourth lamp.

less current flows through the connecting wires, and therefore less of the original voltage is used in sending this current through. A dimming due to fall of potential is often noticed in house lights when an electric iron or toaster is connected to one of the sockets in the same house circuit.

The pressure lost in forcing current through any part of a circuit is called the fall of potential in that part of the circuit. It is measured in volts and can be calculated by the application of Ohm's Law. If R is the resistance of the line wires and I the current flowing through them, then the line drop, e, will equal $I \times R$. The fall of potential, therefore, can be diminished either by reducing the current or by reducing the resistance.

Suppose that a trolley car (Figure 397) takes 200 amperes and the resistance of the circuit between it and the power house is $\frac{1}{4}$ ohm. It will then require $\frac{1}{4} \times 200 = 50$ volts to send this current from the power house to the car. The voltage at the car will consequently be 50 volts less than

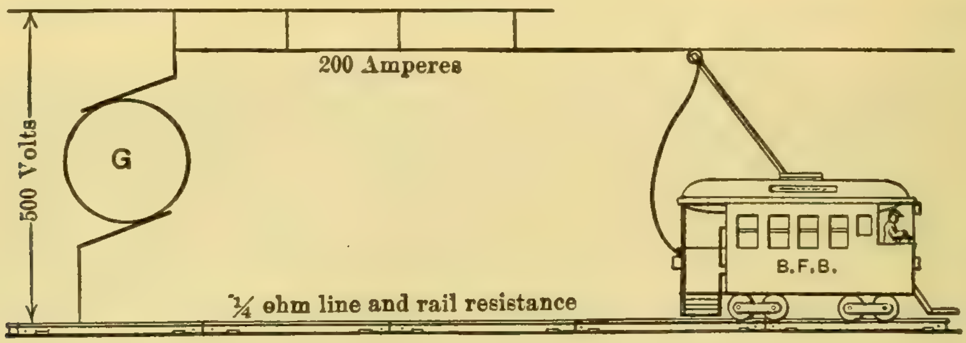


FIGURE 397.—TROLLEY CAR CIRCUIT.

The upper line is a feeder cable, used to reduce the line drop.

that at the power house. When the car is starting, it takes more than 200 amperes from the line, and so the voltage is still further reduced and the lamps grow dimmer. The loss of potential can be reduced by low-resistance "feeder" cables, connected from the power house directly to different points on the trolley line.

The electromotive force of a generator is the total pressure that causes the current to flow through the entire circuit. In each portion of the circuit, part of this electromotive force is used up in the generator itself, the connecting wires, the lamps, or motors, sending the current through that part of the circuit. The sum of these falls of potential in the different parts of the circuit just equals the electromotive force applied to the circuit. We shall see that the wire itself is made of electricity (§ 279), and that the generator merely causes some of the electrons to move along the wire. It is the *pressure* and not the current that is used up in maintaining the flow of electricity through the circuit.

QUESTIONS

1. Are the different parts of an electrical distribution system connected in series or in parallel? Why?

2. In tracing current from a power house to a lamp in your home, what change in the size of wire would you expect to find? What is the reason for this change?

3. What constitutes the greatest item of expense in the ordinary system of electrical distribution? How does the use of alternating current lessen this expense?

4. Is there a change in pressure in an electrical circuit as the distance from the source of pressure increases? What name is applied to this change in pressure?

5. What factors determine the fall of potential in a wire? What is the fall in potential in a wire whose resistance is 5 ohms and in which there is a current of 6 amperes flowing?

6. How does the fall of potential in a circuit affect the brightness of a lamp far from a power house? How are distant lamps prevented from being too dim?

7. How is the pressure in a house circuit affected when an electric heater is connected to the circuit? How would this change of pressure be indicated?

8. Explain what is meant by *fall of potential.* In what units is it measured?

9. A current of 200 amperes is transmitted over a line whose resistance is 10 ohms. What is the voltage drop in the line?

10. A generator, whose pressure is 110 volts delivers 100 amperes to a customer over a line whose resistance is 0.06 ohms. What is the voltage that the customer receives?

262. Wheatstone Bridge. — A very accurate method of measuring resistance, making use of fall of potential, was invented by Wheatstone, an English physicist, in connection with the development of the telegraph. Let us consider first a simple circuit (Figure 398), in which a cell sends current through a divided circuit *AC*. Between the positive end, *A*, and some point, *B*, on the upper wire there is a certain fall of potential. If a flexible wire is connected at *B*

and the other end of the wire is moved along the lower branch, there will be some point, as D, which is as much below the potential of A as B is. If there is a galvanometer in BD, the galvanometer will not be deflected, because there is no difference in potential between B and D. That is, the fall of potential in AB is the same as the fall of potential in AD. This simple circuit illustrates the essential parts of a Wheatstone bridge (Figure 399): four resistances, AB, BC, AD, and DC, connected as shown, and having such values that when A and C are connected to a cell, no current will flow through BD.

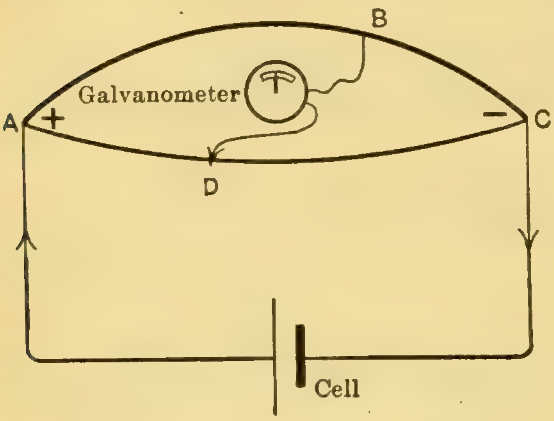


FIGURE 398. — DIVIDED CIRCUIT.

No current passes through the galvanometer, because B and D have the same potential.

Let the current in amperes flowing through ABC be represented by I and that through ADC by I'. The resistances in ohms of each section of the divided circuit may be indicated by R_1, R_2, R_3, and R_4, as shown on the diagram. Then, since the fall of potential in AB is equal to that in AD,

$$IR_1 = I'R_2 \qquad (1)$$

For a similar reason

$$IR_4 = I'R_3 \qquad (2)$$

If we divide equation (1) by equation (2), we obtain

$$\frac{IR_1}{IR_4} = \frac{I'R_2}{I'R_3}$$

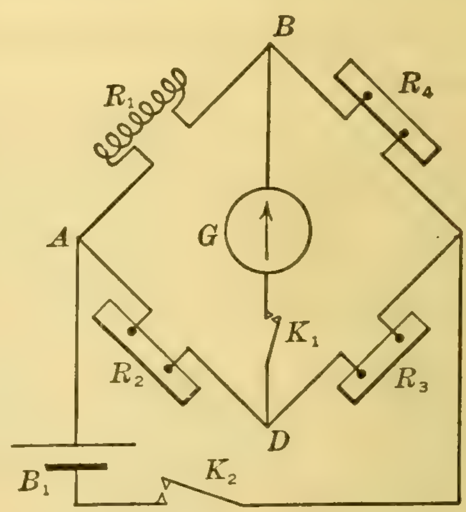


FIGURE 399. — WHEATSTONE BRIDGE DIAGRAM.

R_2, R_3, and R_4, are known resistances; the value of each may be varied. R_1 is the unknown resistance, K_1 and K_2 are keys, G a galvanometer, and B_1 a cell.

This equation may be simplified by canceling I and I' from the two members, giving us the following relation between the four resistances, *when no current flows in BD.*

$$\frac{R_1}{R_4} = \frac{R_2}{R_3}$$

If three of the resistances, as R_2, R_3, and R_4, are known, the unknown resistance,

$$R_1 = R_4 \times \frac{R_2}{R_3}$$

In actual bridges, the resistance of each of the known resistances, or *arms*, is made variable, so that a wide range of unknown resistances may be measured by one bridge. There is also a key in the galvanometer circuit and one in the battery circuit.

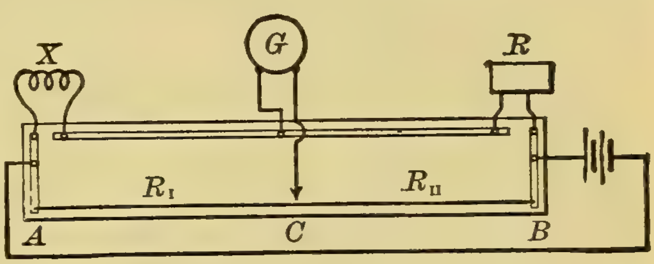


FIGURE 400. — SLIDE-WIRE BRIDGE.

The bridge wire ACB, is stretched over a meter stick between brass blocks. X, G, and R have a common connection in the brass box along the back of the bridge.

The simplest laboratory bridge is the *slide-wire* bridge (Figure 400), in which AB is a high-resistance wire of uniform cross section stretched over a meter stick between heavy brass blocks, A and B. The unknown resistance (X) is connected at A, and at B is connected a *resistance box* (R). This contains a number of coils, made of zero-temperature coefficient wire, connected in series by being soldered to the heavy brass blocks on the top of the box (RB, Figure 401). Any coil may be short-circuited by a taper plug inserted between the blocks to which it is connected. The resistances of the various coils are so selected that any number of ohms, from 1 to 111 or to 1111, may be inserted in the circuit, by taking out

the proper plugs. To use this bridge, plugs are withdrawn from the resistance box, the battery circuit is closed, the free end of the galvanometer wire is touched to the bridge wire, and the galvanometer circuit is closed. If there is a

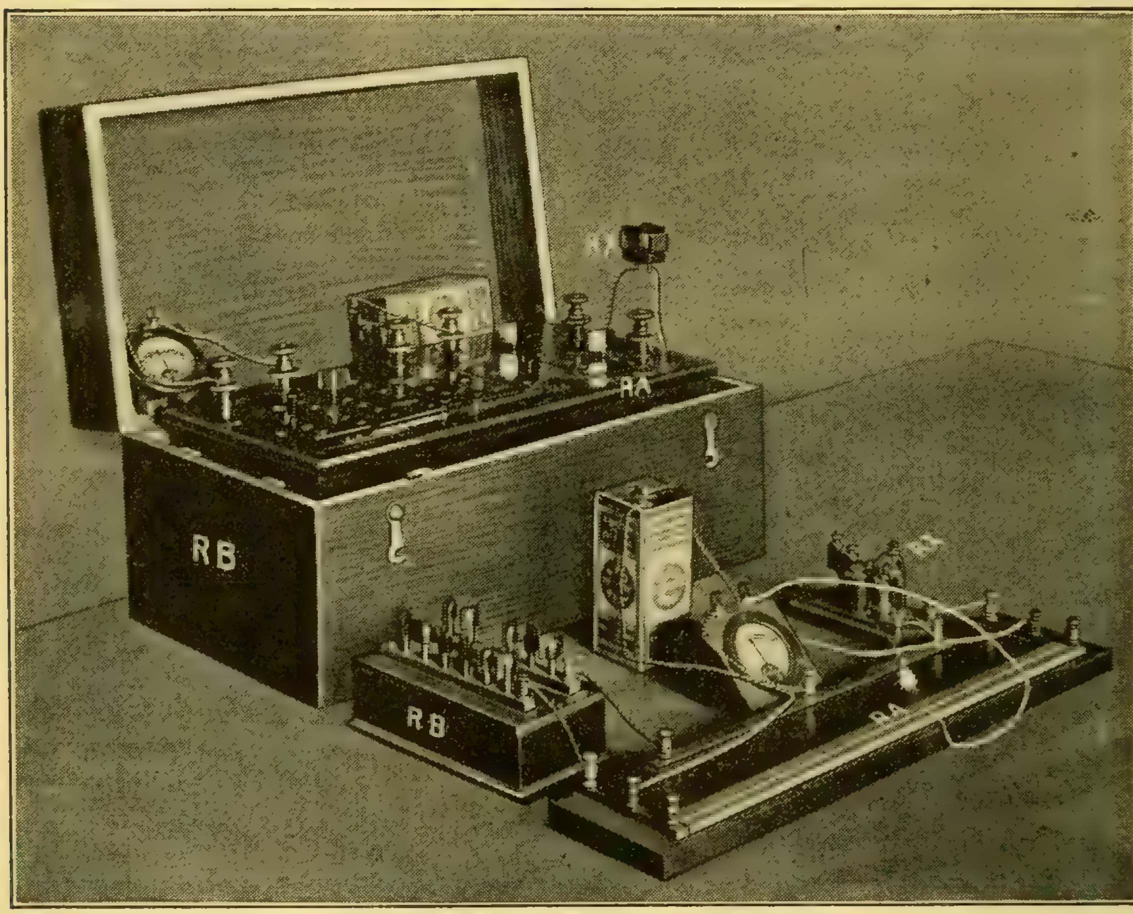


FIGURE 401. — SLIDE-WIRE BRIDGE (FRONT) AND DECADE BRIDGE (REAR).

The unknown resistance on the slide-wire bridge is a telegraph sounder. The decade bridge is very accurate. Its resistance box *RB* is built into the bridge and so connected that four plugs will give any resistance from 1 to 11110. The ratio coils, *RA*, permit measurement to a thousandth or a thousand times the value in the resistance box.

deflection, other points on the bridge wire are tried until a point is found where the galvanometer does not deflect. The bridge is now *balanced*, and the equation may be applied to obtain the value of the unknown resistance. Since the bridge wire is uniform, the ratio between R_3 and R_4 will be the same as the ratio between the lengths AC and DC, and

this ratio of lengths, multiplied by the resistance in the resistance box will give the value of the unknown resistance.

In the *decade* form of the bridge (Figure 401, rear), the case contains, in addition to a set of resistance coils like that described above, two sets of coils, each set having resistances of 1, 10, 100, etc. Permanent connections are made in the box so that these *ratio coils* will have the positions of R_3 and R_4. By inserting one plug in each set of ratio coils, and then balancing the bridge by the use of the other resistance coils, the calculation becomes simply a matter of properly placing the decimal point. This type of bridge is used not only in the laboratory, but also to locate breaks and faults in telegraph and telephone lines.

263. Electrical Power. — Power is the time rate of doing work and the usual unit of mechanical power is the horsepower (§ 404). The power of a water wheel depends on the cubic feet of water per minute that pass through the wheel, but it also depends on the pressure of the water that is supplied to the wheel. In the same way, the power of an electric motor depends on both the current and the voltage. The unit of electric power is the *watt*. The watt is the power in a circuit in which one ampere is flowing under the pressure of one volt. The number of watts in a circuit is equal to the volts multiplied by the amperes, $W = EI$. An electric iron through which 5 amperes is flowing under a pressure of 110 volts is using electric power at the rate of 550 watts. A 40-watt incandescent lamp on a 110-volt circuit takes $\frac{40}{110}$ of an ampere.

As the watt is a small unit, the *kilowatt*, equaling 1000 watts, is used in rating generators and for most other measurements of power. One horsepower is equal to 746 watts, or very nearly $\frac{3}{4}$ kilowatt. This relation is useful to remem-

ber for rapid conversion of kilowatts into horsepower, or the reverse.

264. The Wattmeter. — It is often convenient to measure the power in a circuit directly. The *wattmeter* (Figure 402) consists of two stationary coils (AA), between which is mounted a movable coil (B), with springs (SS), pointer and scale (G), like those in a voltmeter. The stationary coil is of large wire and is connected in series with the line in which the power is to be measured, as an ammeter is connected. The movable coil is of fine wire, usually has a high resistance (R) in series with it, and is connected across the wires supplying the circuit whose power is to be measured, as a voltmeter is connected. The magnetic field of the stationary coil is proportional to the current of the circuit. The magnetic field of the movable coil is proportional to the current through it, and this current depends on the voltage of the circuit, since the coil is connected across the circuit. The force that causes the movable coil to turn is proportional to the product of the two magnetic fields. So by proper design of coils, springs, and scale the instrument is made to read watts directly. Wattmeters are useful on switchboards to show the rate at which power is being furnished at any time.

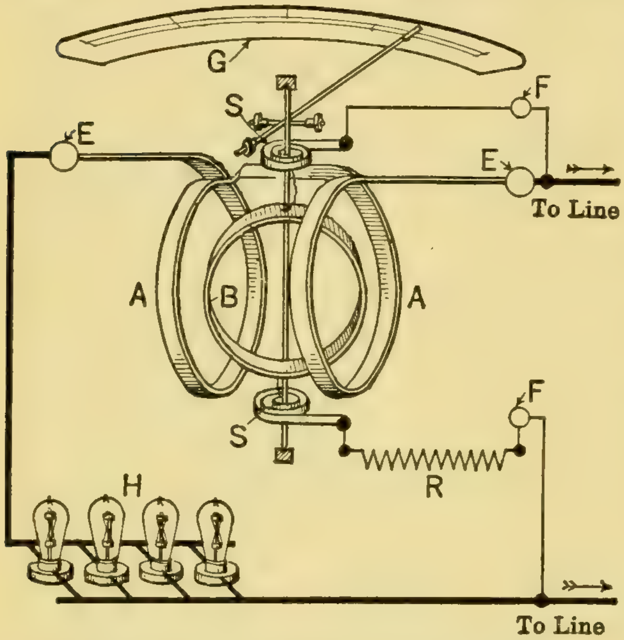


FIGURE 402. — WATTMETER, DIAGRAMMATIC.

H is the load whose power consumption is being measured. The series coil in the actual instrument consists not of one but of several turns.

265. Electrical Work. — The work that a man does depends on how long he works as well as how fast he works; it is the *product* of his working *time* by his working *rate*. So the electrical work for which we must pay the power company depends on both the rate at which power was furnished us (kilowatts) and the hours that we used the power. The unit of electrical work or electrical energy is the *watt-hour* or the *kilowatt-hour*. If we burn 10 60-watt lamps for 3 hours, the electrical energy converted into heat and light is $10 \times 60 \times 3 = 1800$ watt-hours, or 1.8 kilowatt-hours. If this is charged for at the rate of 10 cents per kilowatt-hour, the cost will be $.10 \times 1.8 = \$0.18$.

$$\frac{\textbf{volts} \times \textbf{amperes} \times \textbf{hours}}{\textbf{1000}} = \textbf{kilowatt-hours}$$

$$\textbf{kilowatt-hours} \times \textbf{price per kilowatt-hour} = \textbf{cost}$$

266. Watt-hour Meters. — This is the correct name for the meters installed in our homes which we commonly call "electric meters." The direct-current watt-hour meter has stationary coils (Figure 403, *SC*) and movable coils (*MC*) like the wattmeter. The movable coil, however, has a commutator and brushes like a motor. The meter is in fact an electric motor that drives a train of wheels and axles, like those of a clock. Each of these wheels has 10 times as many teeth as the next axle and is provided with a pointer that moves over a dial. The numbers of the successive dials correspond to units, tens, hundreds, etc., of kilowatts. The faster the movable coil turns and the longer it turns, the larger the number of kilowatt-hours registered on the dials.

Since there are no springs in the meter and the clockwork turns very easily, the meter would " run away " unless there

was some way of opposing the turning force (damping). This means is provided by an aluminum disk (*D*) mounted on the armature shafts, so that it turns between the poles of permanent magnets (*M*). As the disk turns, it cuts across the lines of force of the magnets, thereby inducing an electromotive force. This causes "eddy currents" to flow in the parts of the disk between the magnet poles. These eddy currents produce poles in the disk that oppose the motion, according to Lenz's Law (§ 318). Thus a resisting force is provided that always balances the driving force for any particular power being consumed. For, when the power increases, the armature accelerates, causing the disk to cut the field of the magnet faster than before. This induces larger eddy currents in the disk, quickly making the speed uniform again, but at a higher rate, corresponding to the greater power consumption.

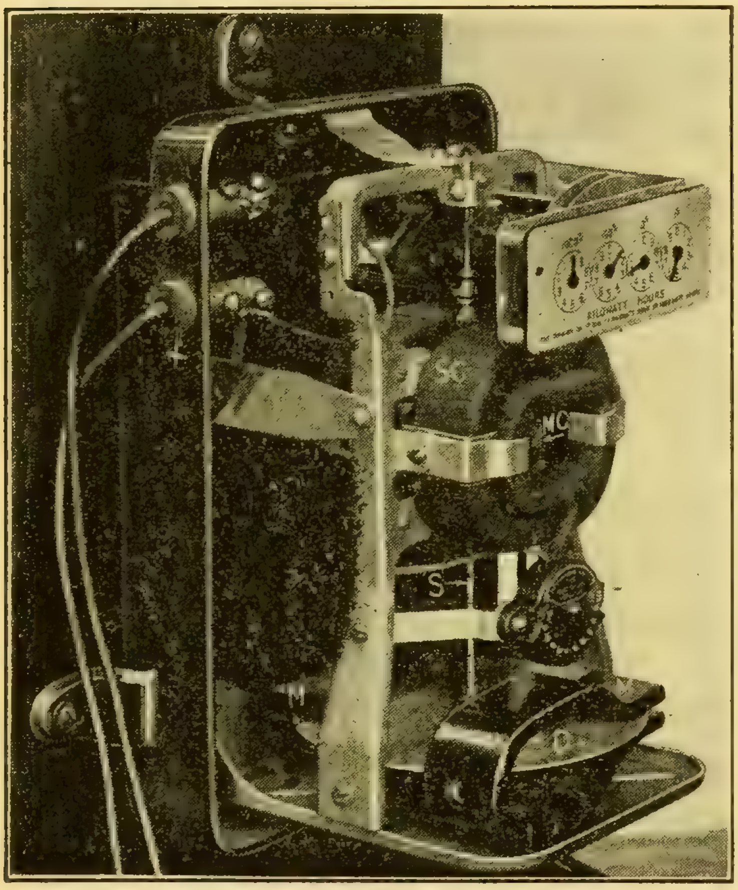


FIGURE 403. — WATT-HOUR METER.

This is really a motor with the field coils in series with the line and the armature coils of fine wire across the line. Eddy currents, induced in the aluminum disk by permanent magnets, keep the speed proportional to the power.

The alternating-current watt-hour meter has a different type of armature and operates on the principle of one type

of alternating-current motor. The alternating-current meter is much more commonly seen, because of the more extensive use of alternating current.

QUESTIONS

1. Make a labeled diagram of a Wheatstone bridge. Write the formula for calculation of the unknown resistance by the use of the bridge that you have drawn.

2. What condition shows that the bridge is "balanced"? Compare the potentials of the two points connected with the galvanometer when the bridge is balanced.

3. With the aid of a diagram, describe the construction of a resistance box. Explain how the desired resistance may be obtained in the box.

4. Upon what law of resistance does the slide-wire bridge depend?

5. In a Wheatstone bridge, the ratio arms are 10 ohms and 100 ohms, respectively, and the resistance box, which is directly connected to the 100-ohm arm, reads 1716 ohms. What is the unknown resistance?

6. A slide-wire bridge is balanced when the contact on the wire is 45 cm from the end at which the resistance box is connected and 65 cm from the other end. The resistance in the box is 25 ohms. Calculate the unknown resistance. Use a diagram.

7. What things about a waterfall determine the rate at which the fall can do work? What would be the customary unit for expressing the rate at which the fall can do work?

8. What two factors determine the rate at which an electric current can do work? What is the customary unit used to express the rate of doing work by electric currents?

9. What is the power of a circuit in which 7.5 amperes are flowing under a pressure of 100 volts? Express your result in kilowatts and in horsepower as well as in watts.

10. How much current, approximately, flows through a 50-watt incandescent lamp when it is connected to a 120-volt circuit? Is *time* an element in expressing the power consumption of the lamp?

11. What is the power of a dynamo when it is delivering a current of 8 amperes at a pressure of 125 volts? Express the result in three different units.

12. State two ways by which the power consumption in a circuit may be measured.

13. When an ammeter in a lighting circuit reads 2.4 amperes and the voltmeter reads 110 volts, what is the power? Make a diagram showing the connection of the instruments in the circuit.

14. Describe the construction of the wattmeter and explain its action.

15. What is a kilowatt-hour? How is the number of kilowatt-hours calculated?

16. How much electrical energy has been utilized in lighting a 50-watt lamp for an hour? For 3 hours? For 5 hours per day for a 30-day month?

17. Is time an element in determining the amount of electrical energy used in operating lamps and motors? Would you expect to pay for the electricity that you use according to the rate at which it is used or according to the amount used?

18. At 10 cents per kilowatt-hour, find the cost of using the lamp in Question 16 for the various times specified.

19. Find the cost of using a 5-ampere flatiron on a 110-volt circuit for 12 hours a month at 10 cents per kilowatt-hour.

20. What other electrical device does a watt-hour meter resemble? What is the field magnet of a watt-hour meter? What is the armature? How would an increase in volts or in amperes affect the motion?

21. Ten 60-watt lamps are burned for 16 hours. What is the cost, if the price paid for power is 9 cents per kilowatt hour?

22. An electric iron takes 4.5 amperes on a 120-volt circuit. What is the cost of operating the iron for 5 hours, when power costs 10 cents per kilowatt-hour.

23. An electric toaster consuming 600 watts is used a half hour every morning. What is the cost per month if the rate is 8 cents per kilowatt-hour?

24. A manufacturer uses an average of 100 amperes at 120 volts 8 hours per day and 300 days per year. At 4 cents per kilowatt-hour, what is his annual power expense for electrical energy?

25. In the watt-hour meter, explain the use of (*a*) the fixed coil; (*b*) the movable coil; (*c*) the aluminum disk.

SUMMARY

An **electric circuit** always includes a battery or some other source of **electromotive force**, and conductors through which the electromotive force causes a **current** to flow. All parts of the circuit have **resistance**, which opposes the flow of the current. The relation between the three quantities is expressed by **Ohm's Law**:

$$I = \frac{E}{R}$$

The **resistance of a conductor depends** on its length, its area of cross section, its material, and its temperature. The **laws of resistance** are:

1. Resistance is **directly proportional** to the **length** of the conductor.
2. Resistance is **inversely proportional** to the **cross section.**
3. Resistance of **metals increases** with the **temperature.**
4. Resistance depends on the material.

The **specific resistance** (k) is the resistance of a wire 1 foot long and 1 mil in cross section. A **mil** is one thousandth of an inch. A round wire having a diameter of 1 mil has an area of 1 **circular mil** ($C.M.$). Hence the area in circular mils is numerically equal to the square of the diameter in mils.

Resistance may be calculated from the above laws by the formula:

$$R = k\frac{l}{C.M.}$$

In **series circuits**, the entire current flows through each part of the circuit. The **resistance of such a circuit** is the **sum** of the resistances of its parts.

In **parallel circuits**, the current divides through a number of paths. The **conductance** of each path, measured in **mhos**, is equal to 1 divided by the resistance of the path. The **total conductance** of the circuit is the **sum** of the conductances of the parallel paths. Hence the resistance may be calculated from the formula:

$$\frac{1}{R} = \frac{1}{r} + \frac{1}{r'} + \frac{1}{r''} + \frac{1}{r'''} + \cdots$$

The **currents in the branches of a parallel circuit** are proportional to the conductances of the branches. If the fractions in the equation above are reduced to a common denominator, the currents in the several branches will be proportional to the numerators of the fractions.

In **power houses**, the generators are usually connected in parallel to bus bars. The **distributing circuits** are also taken off in parallel from the bus bars. The **size of the conductors** is proportional to the currents which they are expected to carry. **Alternating currents** are generally used for power transmission, because the voltage may be raised and the current reduced at the power house by transformers. This permits the use of relatively small line wires. High voltages are reduced by other transformers where the current is to be used.

The **loss of voltage**, caused by sending the current through the line, is called **fall of potential**, or line drop. This may be calculated from Ohm's Law.

In the **Wheatstone bridge**, three variable known resistances and the unknown resistance are connected as shown in the diagram on page 442.

When the resistances have been so adjusted that **no current flows through the galvanometer**, the unknown resistance is calculated from the formula:

$$R_x = R_4 \times \frac{R_2}{R_3}$$

A **resistance box** consists of accurately measured known resistances, so mounted that any number of them may be connected in the circuit. It is used as a part of the Wheatstone bridge, and in other methods of resistance measurement.

Electrical power is measured in watts and kilowatts. The number of watts power in a circuit is equal to the product of the volts and the amperes. $W = EI$

The **wattmeter** consists of a fixed coil, connected in series with the circuit, and a movable coil of fine wire, connected

across the circuit through a suitable resistance. The magnetic field of the fixed coil is proportional to the current and that of the movable coil to the voltage. The movable coil is provided with springs, pointer, and scale like a voltmeter. The angle through which the coil turns is proportional to both the volts and the amperes, so the meter reads directly in watts.

The **work done in an electrical circuit** is the product of the power and the time that the power is used. The unit of electrical work is the **kilowatt-hour.** The **cost** of electrical service is found by multiplying the kilowatt-hours by the price charged per kilowatt-hour.

The **kilowatt-hour meter** has two coils connected like those of the wattmeter. The movable coil, however, has a commutator and brushes, like those of a motor, and drives a train of wheels which carry pointers turning over the dials of the meter. An aluminum disk, mounted on the armature shaft, turns between permanent magnets. The eddy currents induced in this disk make the rate of turning of the armature proportional to the power being used.

EXERCISES

Diagrams of connections will be found helpful in solving the problems.

1. Draw a simple electric circuit, assign values to the voltage and current in the circuit and calculate the resistance of the circuit.

2. State two reasons for making the length of the connecting wires in a circuit as short as possible.

3. The resistance of #10 copper wire is approximately 1 ohm per 1000 feet. The cross section of the wire is halved every 3 numbers. Calculate the resistance of 100 feet of the following sizes: #16, #22, #25, #28, #7, #4, #1.

4. What is the resistance of 250 feet of iron wire whose diameter is 0.05 in?

5. A heating coil contains 125 feet of Climax wire 40 mils in diameter. What is its resistance?

6. A resistance coil is made of manganin wire 20 feet long and 0.012 inch thick. What is its resistance?

7. Why does the field coil of an electric motor take less current after running some time than it does when first started?

8. How does the resistance of carbon change as the temperature increases? When a carbon lamp is turned on, it takes a few seconds to come to full brightness. Explain.

9. Name a material that would be suitable for the coils of a voltmeter. Why?

10. Electric cars are usually lighted with sets of five lamps connected in series. If a lamp is burned out and the socket short-circuited, what will be the effect on the brightness of the remaining lamps? Explain.

11. An electric car takes much more current from the line when it is starting than when it is running. Why are the lamps dimmed during the starting period?

12. The bus bars of a power house supply 4 sets of feeders, the resistances of which are 2 ohms, 4.5 ohms, 9 ohms, and 0.9 ohm, respectively. If the voltage at the bus bars is 120 volts, how much current is being delivered?

13. The resistance of the arc in an arc lamp is 9 ohms. How much resistance must be connected in series with the arc in order to have a fall of potential of 45 volts across the arc when the lamp is used on a 110-volt circuit?

14. What resistance must the shunt of an ammeter have if the resistance of the coil is 1-ohm and 1/125 of the current is to flow through the coil?

15. The same 1-ohm coil is to be used in a 150-volt meter. What is the resistance of the series coil employed if 150 volts send 0.05 ampere through the instrument?

16. A 50-watt lamp, a 20-watt lamp, a 75-watt lamp, and a 100-watt lamp are connected in parallel to a 110-volt circuit. Calculate (*a*) the current through each lamp; (*b*) the resistance of each lamp; (*c*) the total resistance of the circuit.

17. A 25-ohm toaster and a 200-ohm lamp are connected in parallel to the same 110-volt socket. Calculate (*a*) the combined resistance; (*b*) the total current; (*c*) the current through each.

18. A 5-ohm coil and a 100-ohm lamp are connected in series to a 100-volt line. (*a*) What current flows through the combination? (*b*) What is the voltage applied to the coil?

19. Explain why direct current is rarely used for distribution through a town from a central station, but is frequently used in the independent power plant of a building.

20. Why can resistance be more accurately measured by a Wheatstone bridge than by the voltmeter-ammeter method?

21. What values are usually given to the resistances of the ratio coils in a Wheatstone bridge and why?

22. Make a simple labeled diagram of the coils of a watt-meter and show their connection in the circuit.

23. The speed of a watt-hour meter is made accurate by adjusting a resistance in series with the moving coil. Should this resistance be increased or decreased if the meter runs too fast (gives too high a monthly reading)? Explain.

24. Why do the Board of Underwriters limit the amount of current that may be sent through a circuit composed of wire of a given size?

25. Electroplaters use large currents. Why do they employ motor-generator sets giving a small generator voltage instead of reducing the voltage by placing resistance in series between the electroplating bath and the 110-volt line?

CHAPTER XXI

HEATING EFFECTS OF ELECTRICITY

The fact that electric currents produce heat has been mentioned in another chapter, and an experiment that shows this was described in § 84. An electric current cannot flow through any circuit without producing an amount of heat equivalent to the electrical energy expended in moving the current through the circuit. The application of electricity to the production of heat has vastly increased the usefulness of this willing servant of mankind. A glance at this field of usefulness shows that the heat produced by electricity is utilized *directly* for certain definite purposes, and *indirectly* for the light that is emitted by the hot conductors of the current.

267. Where Heat Is Produced in Circuits. — Before the heat effects are discussed, it is necessary to obtain a clear idea of the amount of heat produced in different parts of a circuit. Let us perform a simple experiment to determine this.

Experiment 104. — Connect a piece of No. 22 copper wire to the end of a piece of No. 28 copper wire and send a current of about 5 amperes through them. Which has the higher resistance? *Which becomes hotter?* Consideration of the result of this experiment shows that because more electrical energy is used in pushing the current through the fine wire, more heat is produced in it. In general terms, *that part of the circuit where the resistance is the greatest will be the hottest.*

A second experiment indicates a fact that is apparently contradictory, but this second fact must be grasped before the use of heating devices is well understood.

Experiment 105. — Fill two jars with equal amounts of cold water, so that when an incandescent bulb is inserted in each, the water will just cover the bulb. In one jar put a 32 c.p. carbon lamp. This lamp has a resistance of about 125 ohms and allows about 1 ampere of current to pass through it. In the other jar put a 16 c.p. lamp which will have a resistance of 250 ohms and will allow about $\frac{1}{2}$ ampere to pass through it (Figure 404). Attach the lamps to a 110-volt circuit and let current pass through until the water is warmed perceptibly. Then measure the temperature of the water in each jar. The water in the jar containing the lamp of the lower resistance will be found to be much warmer. In this lamp the current has found an easier path to travel and consequently a larger stream flows through this path, thereby requiring a greater expenditure of electrical energy to maintain this larger stream. In the 250-ohm lamp a more difficult path is encountered, hence a smaller stream flows and less energy is transformed into heat in pushing this smaller stream through the lamp.

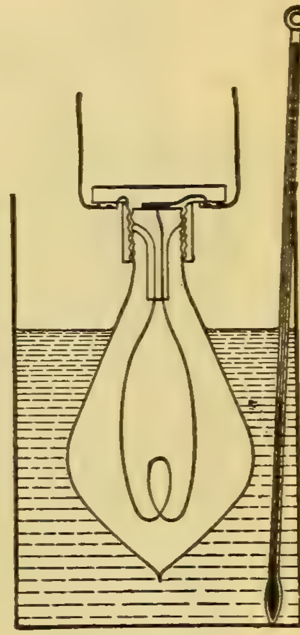


Figure 404.

Let us compare the results of these two experiments. In the first we find that in a single circuit, made up of different conductors, the hottest portion of the circuit will be where the resistance is greatest. In the second experiment we find that of two circuits having the same pressure the one having the less resistance will produce more heat, because a larger stream of electricity passes through it.

It is a mistaken idea that heating devices are always of high resistance. If a heating device does have a high resistance, it is either to reduce the cost of operation or to prevent a dangerously large current from flowing through the device.

268. The Carbon Arc. — One of the common devices that produce heat by the expenditure of electrical energy is the carbon arc. Attach two carbon rods to a 110-volt circuit

through a resistance that will allow 15 to 20 amperes to pass through the rods. Hold the rods by insulating handles behind a shield of colored glass and touch the tips together (Figure 405). Since the resistance of the circuit is greatest at the point of contact, this point will produce the greatest heat. The contact will glow with an intense light. The heat generated is sufficient to vaporize the carbon and this hot vapor is itself a conductor. The carbons may be separated nearly an inch and current will still flow across the gap by means of the carbon vapor. The tips of the carbon and the hot gas between them glow with the most brilliant artificial light that has been produced. The positive carbon tends to form a crater at its tip and this crater is the hottest thing that man has been able to devise.

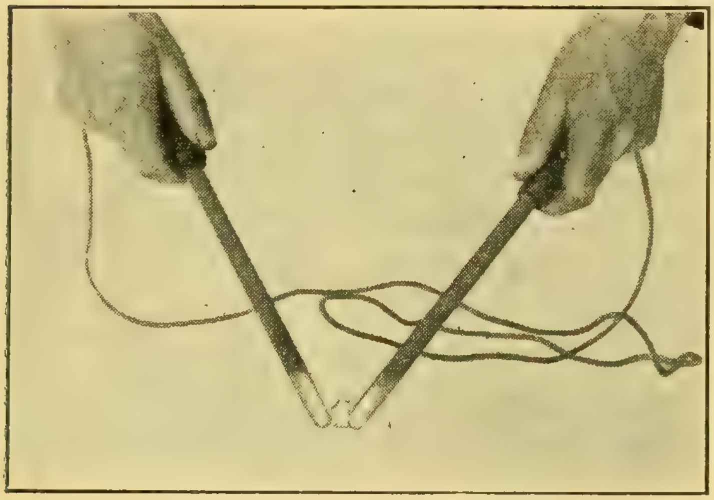


FIGURE 405. — CARBON ARC.
The carbons are wound with insulating tape at the upper end.

The carbon arc, originally designed for a lamp, has gradually shifted its field of usefulness from illumination to heating. In arc furnaces (Figure 406), large carbon rods carrying currents of great amperage are inserted through walls of firebrick. The intense heat generated is sufficient to melt the most refractory substances. Steel and a great variety of alloys are now often made by this process.

269. The Arc Lamp. — The carbon arc lamp was first used for illumination and is still in use for this purpose to

some extent. For street lighting, the lamp carbons are put in a straight line with the positive carbon above. An ingenious electromagnetic sucking coil allows the carbons to touch when the current is off (Figure 407). As the current

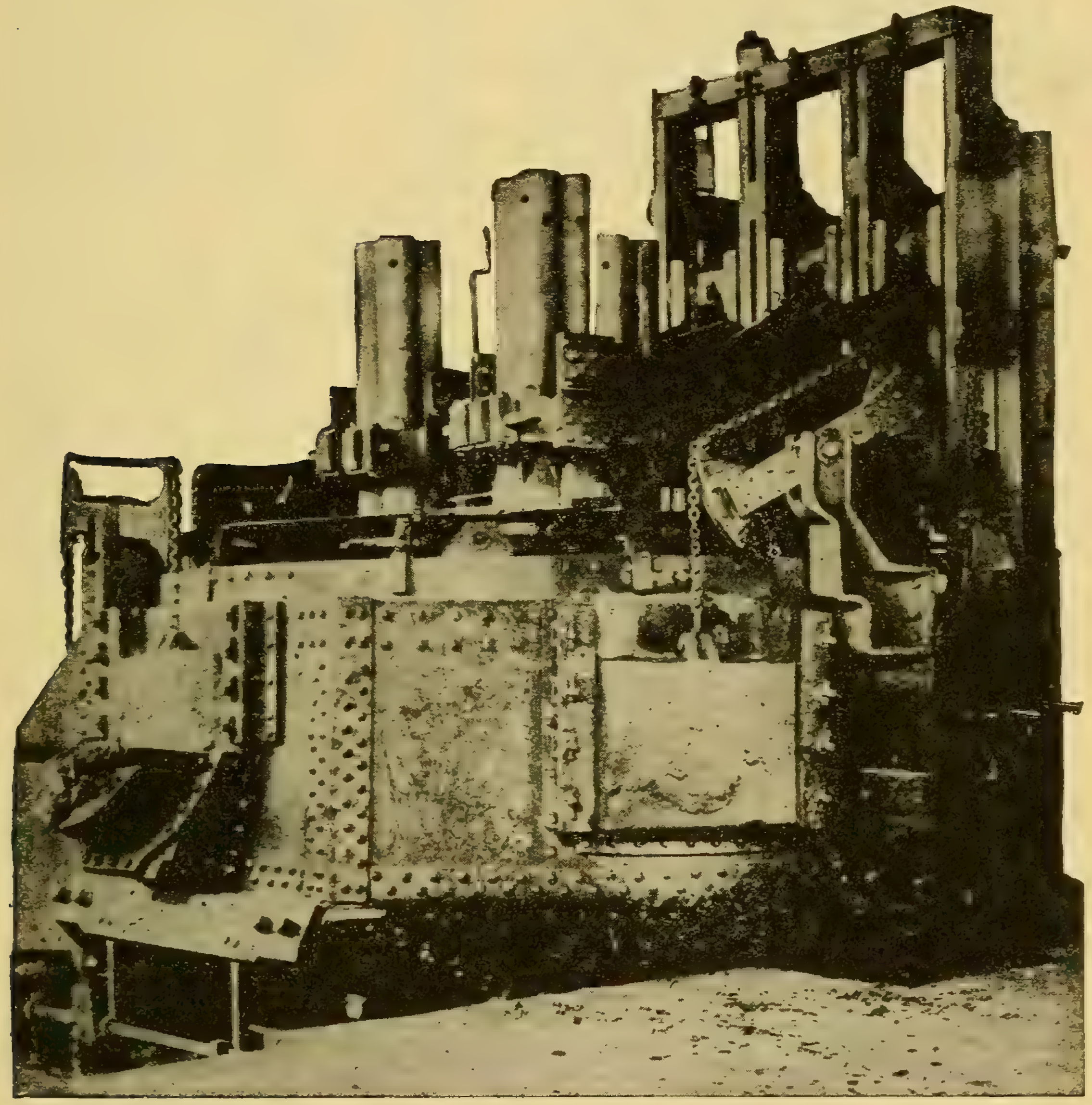


FIGURE 406. — HEROULT ELECTRIC FURNACE FOR STEEL.

Note the large size of the two carbons in the center of the picture. The heat of the arc between them permits a rapid change of the charge into steel.

is turned on, the magnet draws the upper carbon about one half inch away from the lower one and maintains this gap as the carbons slowly vaporize. The carbons do not burn away, but are converted into a gas by the intense heat.

This necessitates replacing the carbons at frequent intervals. The more convenient and less cumbersome gas-filled incandescent lamp is replacing the arc lamp for street lighting. The arc is now much used in moving-picture machines because of its intense light, but even here its place is being taken to some extent by the incandescent lamp.

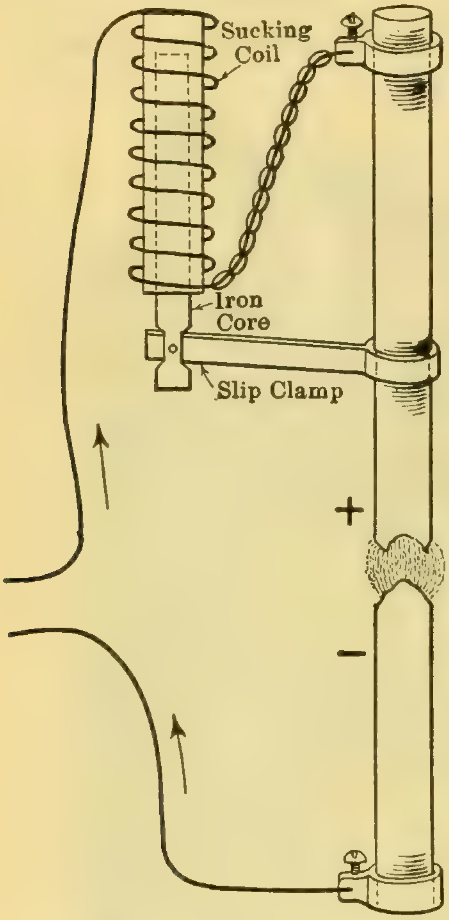
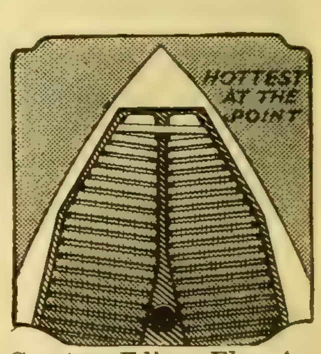


FIGURE 407. — ARC LAMP.

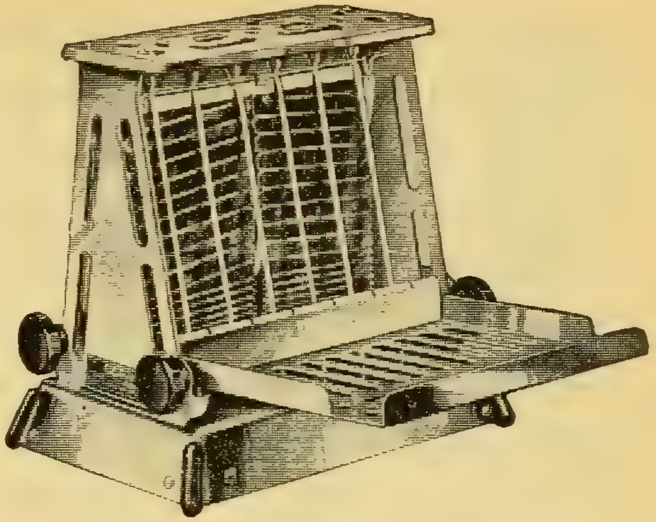
The clamp fits loosely around the upper carbon, but lifts it when the current draws the core into the coil. As the arc lengthens, the current decreases and the carbon slips down.

270. Other Electric Heaters. — Electric heating devices of various forms are in common household use. Flatirons (Figure 408), toasters (Figure 409), coffee percolaters, water heaters, and even entire cooking ranges are equipped with coils of special alloy wire having a high melting point and no tendency to oxidize at red heat. Current is sent through these coils and the heat produced is used for the purposes mentioned. Referring to § 267 we see that to obtain a great amount of heat, a coil of low resistance should be used. This permits a larger current to flow and therefore increases the cost of operation. For a device where little heat is needed, as in a curling-iron, a high-resistance coil is used with a correspondingly low cost.



Courtesy Edison Elec. Appliance Co.

FIGURE 408. — RESISTANCE STRIP OF ELECTRIC IRON.

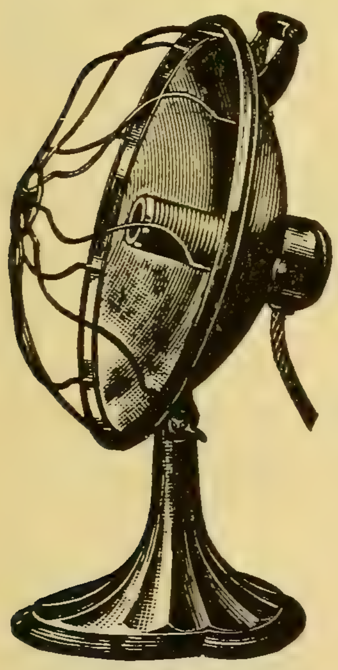


Courtesy Edison Elec. Appliance Co.

FIGURE 409. — TOASTER.

Wire of high resistance, not easily oxidized, is used.

Electric energy is too expensive to be used extensively for the heating of buildings. In fact, the chief arguments for its use in any heating device are that it is clean, convenient, and readily applied to the place where heat is needed. Electric heaters, however, are used to heat individual rooms (Figure 410), and street cars are usually warmed by such heaters because other heating devices would not be safe or convenient. There is no present reason for believing that electricity will ever be cheap enough to use for general heating purposes.



Courtesy of Edison Elec. Appliance Co.

FIGURE 410. — RADIANT HEATER.

The heating coil is placed in the focus of a copper reflector.

271. Incandescent Electric Lamps. — Many efforts have been made, with varying success, to use electrically produced heat for purposes of illumination. In each device, a substance was heated to incandescence by electricity and this incandescent body emitted light. The arc lamp was one of the early attempts at electric lighting, but its light was too powerful for domestic use, besides being variable and uncertain. In later lamps efforts were continued to heat a substance to incandescence without oxidizing it or vaporizing it. Oxidation could be pre-

vented by inserting the heated substance in a vacuum, or later in an atmosphere of nitrogen and argon. Vaporization is reduced by using a substance whose melting point is above the temperature at which it emits white light.

The first successful substance to be used was a filament or thread of carbon. This thread was looped in a glass bulb from which the air had been removed. One end of the filament was attached to the bottom of a brass base, the other end was attached to the insulated side of the base (Figure 411). Contact was made with the circuit by means of a socket into which the lamp base screws. As current passed through the filament, the filament became heated to incandescence and thus emitted light. If enough current passed through to make the filament white hot, the carbon vaporized too rapidly. Thus the bulb was coated on the inside with a deposit of carbon that absorbed much of the light, and the filament was thinned until it finally broke. A yellow light was obtained at the expenditure of a large amount of electrical power (3.5 watts) per candle power.

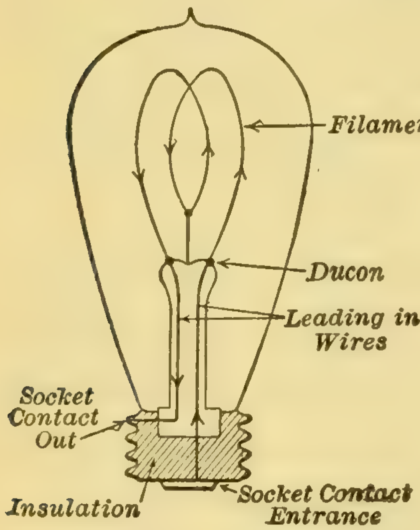
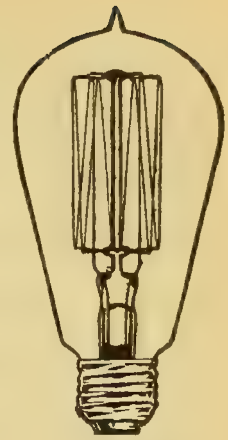


FIGURE 411. — CARBON LAMP.

Ducon is an alloy that expands at the same rate as glass.

272. Metallic Filaments. — At the time when the carbon lamp came into use, little was known of the physical properties of certain rare metals. Investigation of some of these showed that they had properties suitable for the filament of an incandescent lamp. Of the many that were tried, tungsten has proved the most successful, because of its high melting point, great resistance, and a reasonable degree of

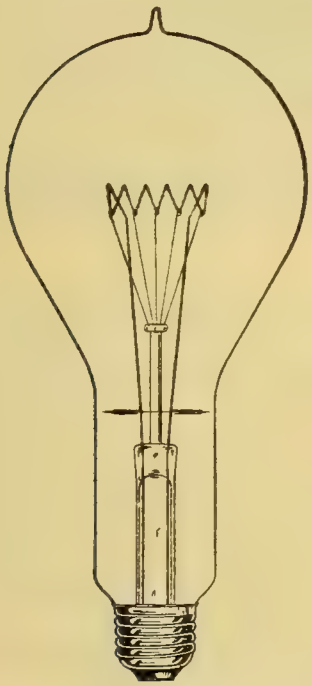
tenacity. Tungsten can be drawn into very fine wire that has high resistance and it can be heated without vaporizing until it gives a light that is nearly white. It therefore gives a better as well as a more economical light. The power consumption per candle power of a tungsten filament lamp is only a little over 1 watt. (Compare with the carbon lamp on page 462.) Tungsten lamps (Figure 412), often sold under the name "Mazda," have been constantly improved in quality, mainly by bettering the tenacity of the wire filament. They are at present the most widely used form of incandescent lamp.



Courtesy of Edison Lamp Co.

FIGURE 412.—TUNGSTEN FILAMENT LAMP.

273. Gas-filled Bulbs. — It has been the aim of each change in lamp construction to obtain a filament that could be heated to a higher temperature without vaporizing. This produces a whiter and cheaper light. Within the last few years, lamps having a tungsten filament inserted in an atmosphere of nitrogen and argon (Figure 413) have appeared on the market. The pressure of these gases permits a higher temperature of the filament to be attained without vaporization. As each increase in temperature raises the efficiency of the lamp and also improves the quality of the light, these lamps are becoming increasingly popular. They vary in power consumption according to size, the large lamps requiring only $\frac{1}{2}$ watt per candle power and the smaller ones about 1 watt per candle power.

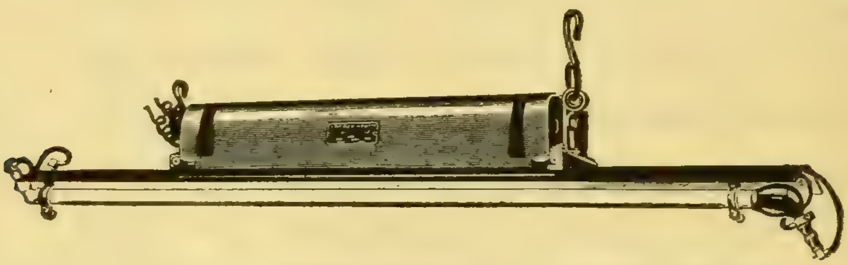


Courtesy of Edison Lamp Co.

FIGURE 413.—NITROGEN LAMP.

The gas permits higher temperature and whiter light.

274. Other Lamps. — A great many other types of lamps have been devised at various times but some defect or limitation has prevented their general use. One of these, the Cooper-Hewitt mercury-vapor lamp (Figure 414), has an efficiency which compares favorably with the types considered above. This type of lamp is used in photographers' studios, because it is rich in ultra-violet light, and in many manufacturing establishments where illumination is more important than color values. The light, being more nearly of one wave length, focuses more sharply and permits clearer vision.



© *Courtesy of G. E. National Lamp Works.*

FIGURE 414. — MERCURY VAPOR LAMP.

The arc extends the whole length of the tube. The box above contains resistances and switches.

The future will see a great extension of the use of electricity for lighting purposes because of its convenience and relative cheapness. As indicated, however, there is little likelihood of electricity's being used extensively for general heating unless the cost of electrical energy is reduced to a small fraction of the present charge.

275. Fuses. — Electrically generated heat is used as a safeguard against an oversupply of heat from the same source. The explanation of this apparently contradictory statement is found in the use of fuses. A fuse is a piece of lead or lead-alloy wire placed directly in the circuit to be protected (Figure 415). Lead is used because of its low melting point.

Suppose your house to be wired with copper wire thick enough to carry only 10 amperes without overheating. At the point where the service wires are connected to the house wires, the electrician sets in each wire a piece of lead wire inclosed in a case like the base of an incandescent lamp. These lead wires are thick enough to carry 10 amperes with-

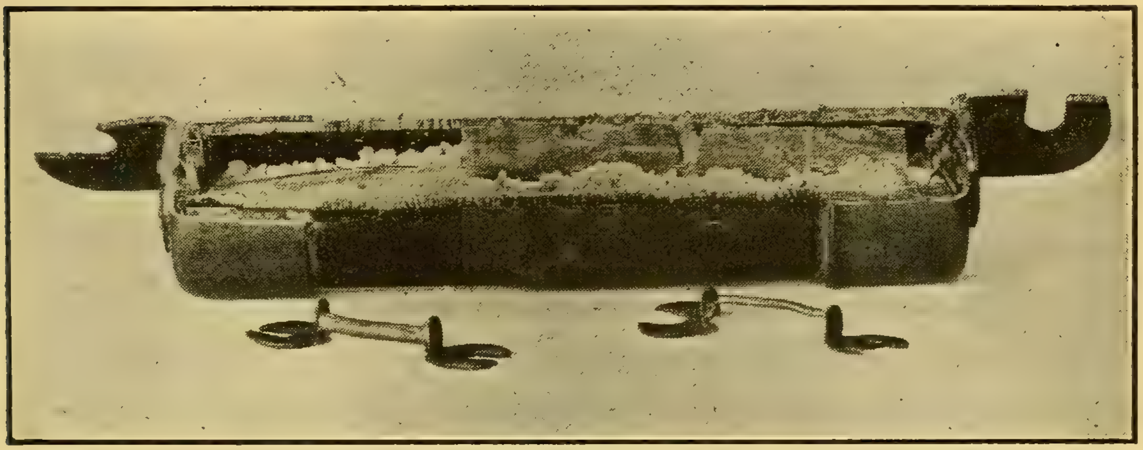


FIGURE 415. — ELECTRIC FUSES.

Bare fuses for 5 and 15 amperes are seen in front of a sectioned 200-ampere fuse. The strip of fusible alloy in the latter is packed in heat-insulating powder.

out melting, but will melt if you accidentally cause more than 10 amperes to flow through the house circuit.

When the fuse melts, the current is stopped, so no damage is done to the house wiring and there is no danger of fire. A new fuse must be inserted after the wrong connection is rectified, but the melting of the fuse worth a few cents has saved many dollars. Fuses are generally incased in fireproof boxes to prevent the melted lead from setting fires. They may be purchased in any size from 1 or 2 amperes up to those able to carry hundreds of amperes, and in a variety of shapes. Their use is the same as the magnetic circuit-breaker (Figure 358), but a circuit-breaker is used only when the constant breaking of the circuit by melted fuses would

make the cost of replacing the fuses excessive. The fuses are used only when an occasional accident could "blow" them, so the larger first cost of the circuit-breaker is thus avoided. Thus it is seen that the fuse is a safety valve by which some heat generated in a circuit automatically shuts off the current and prevents the production of too much heat.

276. Heating Calculations. — Since the development of heat in an electric circuit depends on the consumption of electric power in overcoming resistance, we may expect the rate at which heat is developed in the circuit to be proportional to the power consumption. The amount of heat energy obtained will depend on the time as well as the power. It is found that the heat produced, measured in calories, is equal to the watt-seconds multiplied by the constant 0.24. If H stands for the heat in calories, and t for the time in seconds, then

$$\mathbf{H = 0.24\ EIt}$$

Since the fall of potential in the heating unit, E, is equal to the current, I, multiplied by the resistance of the heater, R, the equation may be written:

$$\mathbf{H = 0.24\ IR \times I \times t = 0.24\ I^2Rt}$$

This second form of the equation is the one generally used, because if the resistance of the heater is known, it will only be necessary to use an ammeter to measure the current and a watch to measure the time. This equation is also useful in measuring the *losses* in transmitting current through a conductor or a piece of electrical apparatus, since these losses appear as heat. Hence such losses are often spoken of as I^2R losses. It is this loss of energy in the wires of the transmission line which limits the economical transmission of electrical energy to relatively short distances.

SUMMARY

Electrical energy is used to produce heat for the sake of the heat itself and for the light emitted by the heated bodies. The heat energy produced is equal to the electrical energy utilized.

Heat is produced **in an electric arc** furnace or in coils of wire. A **low-resistance coil** allows more current to flow and therefore **produces more heat** than a high-resistance coil, when both are connected to a circuit of given voltage.

Incandescent lamps commonly have a fine tungsten wire inserted in a glass bulb, which surrounds either a vacuum or an atmosphere of nitrogen. The electrical energy required to push current through this filament is converted into heat, causing the filament to emit a nearly white light.

Fuses are pieces of lead wire, connected in series in a circuit, which melt and shut off the current when more than a specified current passes through them.

The **heat generated in an electric circuit** is proportional to the electrical work done. The heat in calories is found from the equation:

$$\textbf{Calories} = \textbf{0.24 watt-seconds} = \textbf{0.24}\ \mathbf{I^2Rt}$$

Transmission losses due to resistance are calculated by this equation.

EXERCISES

1. Describe an experiment to show that heat may be produced by electricity.

2. Electric current is distributed through the streets of a city through large (low-resistance) copper cables. Houses are wired with copper wire about the size of pencil lead. Incandescent lamps have a wire as fine as a hair. When the same current flows through each of these conductors, where will the most electrical energy be used and where will the most heat be produced?

3. Two incandescent lamps of 240 and 360 ohms resistance respectively are connected to a 120-volt source of current. Which lamp will allow more current to flow? Which will emit more heat and light energy? Which will cost more per hour?

4. Describe a carbon-arc furnace or lamp. Why is it used?

5. Describe some form of electric heating device suitable for domestic use. What kind of wire should it have? What determines the amount of resistance it should have?

6. Why is tungsten a suitable metal for use in lamp filaments? Why is the air exhausted from the bulbs of some lamps?

7. What form of incandescent lamp is replacing the vacuum bulb lamp? Why is this change an improvement?

8. How does a 60-watt lamp differ in construction from a 25-watt lamp?

9. Discuss the probable future of the extension of the use of electricity for heating. Give reasons for your opinions.

10. What arguments are in favor of the use of electricity for heating?

11. Of what material are fuses made? Why?

12. How would you connect fuses in a circuit? Illustrate by diagram.

13. Compare fuses with circuit-breakers as to general use; first cost; cost of making the circuit usable after having been overloaded.

14. How does a 5-ampere fuse differ from a 50-ampere fuse? Explain why.

15. Would you put fuses or a circuit-breaker in a house circuit? Why?

16. Would you put fuses or a circuit-breaker in a trolley-car motor circuit? Explain.

17. What determines the size of the fuse to be used in a given circuit?

18. Give the equation for calculating the heat produced in an electric circuit, and state the meaning of each symbol and the unit in which it is measured.

19. Why are transmission losses called "I^2R losses"?

20. A current of 100 amperes is delivered by a generator whose terminal voltage is 110 volts through a line whose resistance is 0.05 ohm. Calculate (*a*) the voltage at the end of the line; (*b*) the power loss in the line; (*c*) the percentage of power delivered to the customer.

21. In an electric percolator, 200,000 calories are required to make the coffee. How much electric energy is used?

22. An electric heater has a resistance of 10 ohms and requires 12 amperes of current. How much heat will it produce in half an hour?

23. A room is lighted by 10 incandescent lamps on a 110-volt circuit, each lamp requiring 0.5 ampere. How much heat is developed in the lamps in 2 hours?

CHAPTER XXII

ELECTRONS

In a previous chapter it has been stated that the nature of electricity is still a matter of theory and conjecture. Much has been done during the past generation, however, in the establishment of a theory that gives a working explanation of the great mass of facts and phenomena that have been experimentally determined. An important feature of this theory is that it also goes far toward the unification of our knowledge of chemical action and the nature of matter.

277. Electrified Bodies. — The Greeks discovered that amber, when rubbed, would attract light bodies, and from their word for amber our word "electricity" is derived. Benjamin Franklin made very extensive experiments in the electrical action of various substances when rubbed together, and to him we owe the terms *positive* and *negative* electricity.

Experiment 106. — Rub briskly a rod of hard rubber with cat's fur. By this action, the rod is said to have been *electrified.* Bring the rod near cork filings, bits of tissue paper, or bits of aluminum foil (Figure 416). *What is the effect of the electrified rod on light pieces of material?*

Experiment 107. — Test in the same way a rod of dry, warm glass that has been rubbed with silk. *Is the glass rod also electrified?*

Experiment 108. — Suspend by a silk thread a light stirrup of paper or insulated wire. In this, balance a wooden rod about 2 feet long and $\frac{1}{4}$ inch in diameter. When it has come to rest, electrify the glass rod and bring it near the wood, without touching it. *Result?* In the same way test the electrified rubber rod. *Result? Of what experiment in magnetism does this remind you?*

It should be noted that in these experiments the materials used are all non-magnetic. The results show that *electrified bodies attract unelectrified bodies.*

FIGURE 416. — AN ELECTRIFIED BODY ATTRACTS LIGHT OBJECTS.

278. Two Kinds of Electrification. — Let us next experiment with the action of electrified bodies on each other.

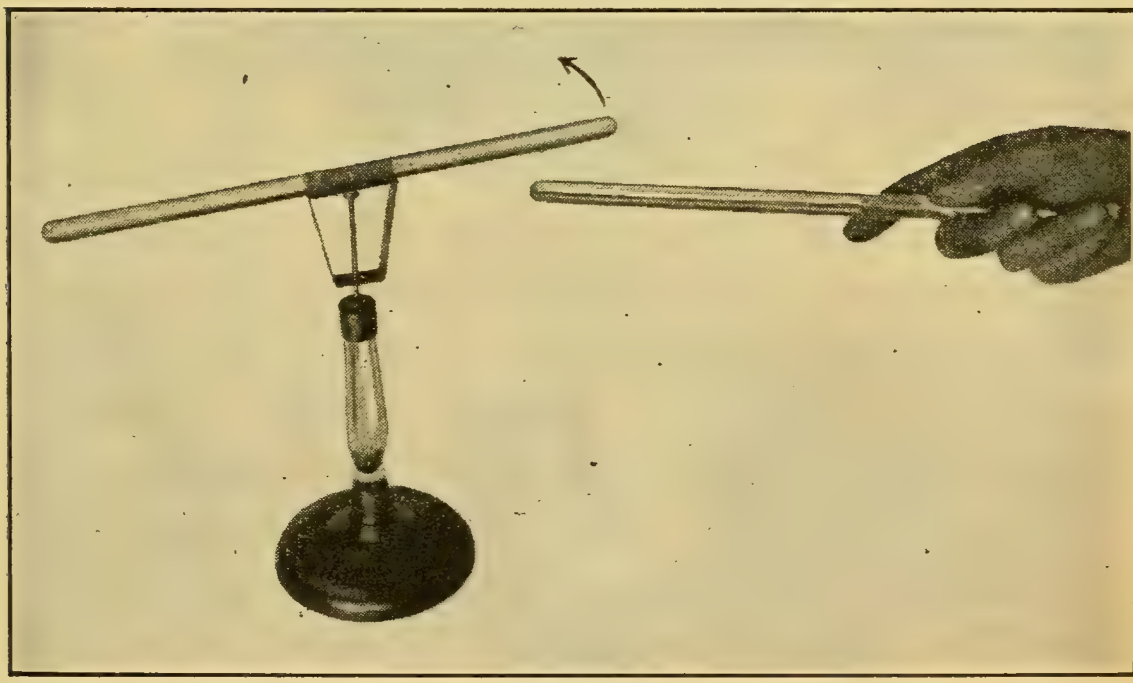


FIGURE 417. — SIMILARLY ELECTRIFIED RODS REPEL.

EXPERIMENT 109. — Electrify a glass rod with silk and carefully balance it so that it can turn freely. Bring another electrified glass rod near the suspended rod and observe the action (Figure 417). Next test the balanced electrified glass rod with a rubber rod electrified with flannel (Figure 418). Then suspend an electrified rubber rod and test it with another electrified rubber rod and with an electrified glass rod.

The results of this experiment are:

(1) Electrified glass repels electrified glass and attracts electrified rubber.

(2) Electrified rubber repels electrified rubber and attracts electrified glass.

As a result of many such experiments with various substances, Franklin concluded that there are two kinds of electrification, or better, two kinds of electricity. Bodies that behave like the electrified glass he said possessed *positive* electricity, and those behaving like the rubber, *negative* electricity. Any substance that can be electrified in the manner described above he called *an electric;* our modern name for such a substance is an *insulator.* After an insulator has been electrified, the electricity does not move through the insulator as it would through a conductor; electricity standing or remaining stationary on an insulator is called a *static charge, static electricity,* or simply a *charge.*

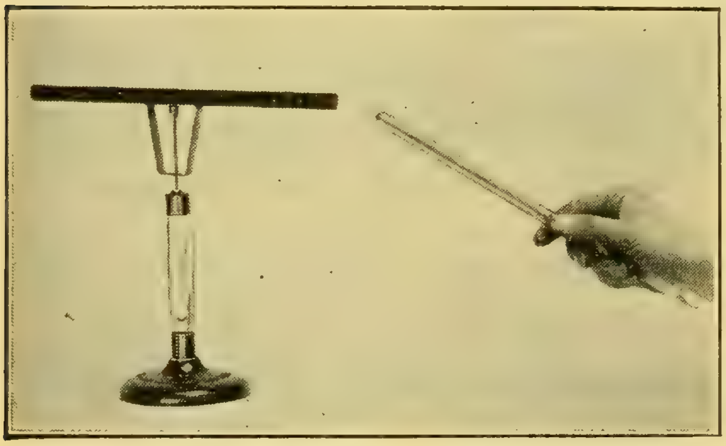
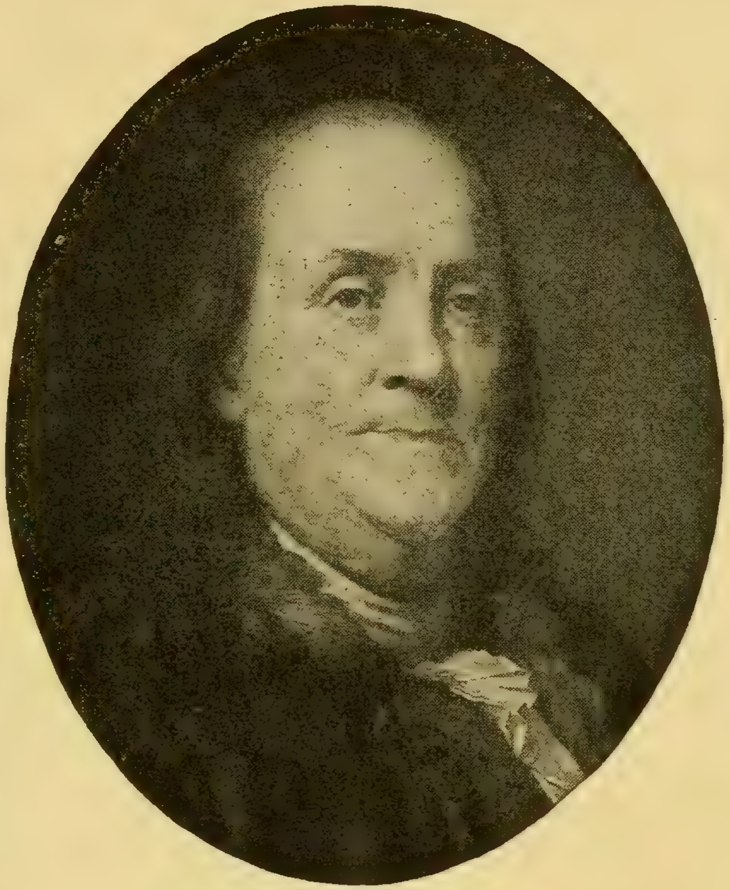


FIGURE 418. — OPPOSITELY ELECTRIFIED RODS ATTRACT.

Using these new terms, we may summarize all of our results thus: *Like charges repel; unlike charges attract.* The similarity of this statement to that regarding magnetic poles is apparent.

279. The Electron Theory. — For more than a century after Franklin's experiments theories of the nature of electricity were advanced, only to be discarded as they were found insufficient to explain all the facts. Out of a mass of



Benjamin Franklin (1706–1790) is much better known as an editor, philosopher, statesman, and diplomat than as a scientist. It is likely, however, that only the pressure of his official duties kept him from devoting the latter part of his life to scientific research. Franklin did render one peculiar aid to science, which probably could not have been surpassed. He was one of the best known men of his time and, when he proved with his kite that the electricity of the Leyden jar and that of lightning were the same thing, his popularity turned the minds of the world to the conquest of nature by science. Besides the stimulating effect of his personality, Franklin contributed our present theory of two kinds of electricity and made practical improvements in agriculture, heating, lighting, navigation, medicine, and hygiene.

investigation of the most diverse sort has come the electron theory, universally held to-day by men of science. According to this theory, all matter consists of positive and negative electricity. Every atom of every element contains both (Figure 419). If a body is unelectrified, it consists of equal amounts of positive and negative electricity. If it is negatively electrified, it has *more negative* than positive electricity; if it is positively electrified, it has *less negative* than positive. It will be noted that emphasis has been given to *negative* electricity rather than to positive. This is because hundreds of most ingenious and patient experiments all point to the conclusions: (1) that negative electricity exists in the form of tiny particles called *electrons;* (2) that the action of static charges is due to an excess or deficiency of these electrons; (3) that the motion of electrons constitutes an electric current in a metallic conductor; and (4) that the difference in the chemical elements is largely due to the number and arrangement of the electrons present. These are the cardinal points in the electron theory.

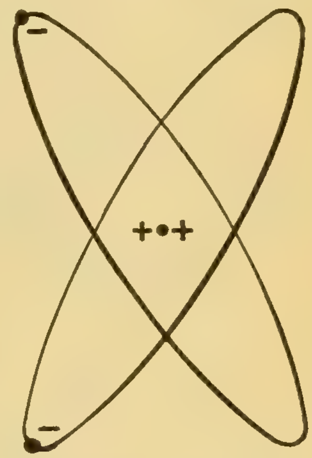


FIGURE 419. — HELIUM ATOM, ACCORDING TO BOHR. Two unbound + charges in the nucleus are balanced by two electrons rotating in ellipses.

Let us now try to get as definite an idea as possible of what an electron is and we shall then be able to give the electron explanation of various phenomena.

280. Nature of Electrons. — Every atom consists of a nucleus containing an excess of positive electricity, of whose form and nature we know little, and from one to ninety-two electrons moving around this nucleus (Figure 420). By various means electrons may be separated from the atoms, and to these free electrons all electrical actions and effects

are due. From whatever source they come, every electron is exactly like every other electron. The mass of an electron, or particle of negative electricity, is found to be about one eighteen-hundredth that of the hydrogen atom. So small is it that its diameter is only one hundred-thousandth the diameter of the atom. The relative sizes of the electron and the atom are that of a grain of dust and a house. When freed from the atoms, electrons are subject to the same forces and actions as are the larger negative charges composed of them, which we have been experimenting with. Two negative charges that, when placed one centimeter apart, would repel with a force of one gram, would each contain more than two trillion electrons.

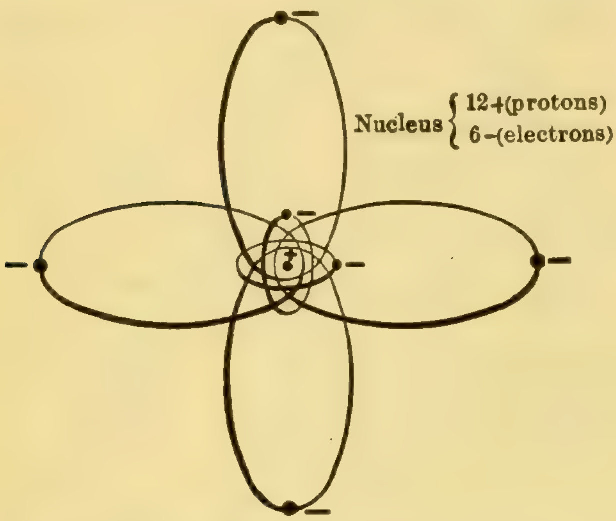


FIGURE 420. — CARBON ATOM.

Six electrons are in the nucleus and the other six rotate in orbits like those shown.

281. The Electroscope. — The suspended wooden rod used in Experiment 108 affords a method of showing the presence of relatively large electric charges, but it is not very sensitive and does not identify the nature of the charge brought near it. The *gold-leaf electroscope* (Figure 421) may be used to detect the presence of very small electric charges, to show whether they are positive or negative, and to compare the amounts of the charges. A brass rod has a brass disk or knob soldered to the top, and to the bottom are fastened two strips of gold leaf, about an inch long, in contact with each other when uncharged. For protection against air currents, the rod is set through an insulating stopper in a glass con-

tainer. Any electric charge, either negative or positive, communicated to the knob spreads over the disk, the rod, and the gold leaves, because they are all conductors. Since the gold leaves have like charges, they will repel each other, swinging out to form an inverted V. The amount of separation will depend on the amount of the charge.

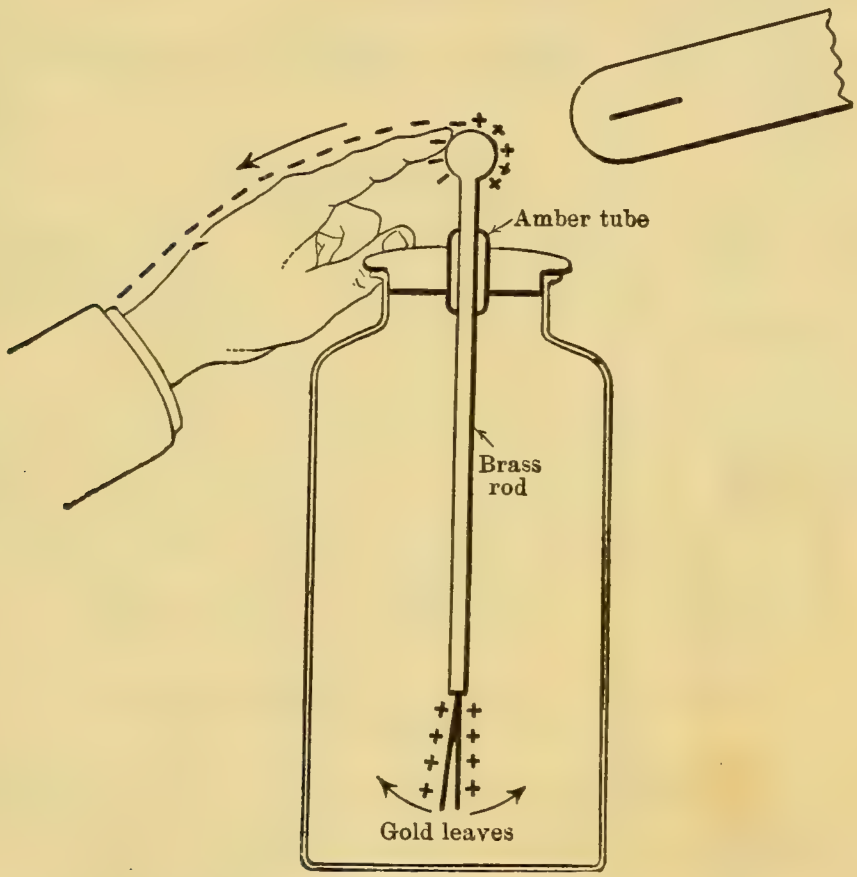


FIGURE 421. — GOLD LEAF ELECTROSCOPE.

It is shown receiving a + charge by induction.

282. Charging the Electroscope. — The best method of charging the electroscope is by *induction*, as follows:

1. Bring a positively charged glass rod near, *but not touching*, the knob. The leaves diverge (Figure 422, *A*).

2. Holding the glass rod in place, touch the knob with the finger. The leaves collapse (Figure 422, *B*).

3. Withdraw first the finger, then the glass rod. The leaves diverge with a *negative* charge (Figure 422, *C*).

A *negative* charge brought near the knob will cause the leaves to diverge more widely. If hard rubber, rubbed with flannel, is used to charge the electroscope, the charge on the leaves will be a *positive* one, and another positive charge brought near the plate, will cause greater divergence of the leaves.

283. Explanation of the Electroscope. — When the positively charged glass rod was brought near the knob, free

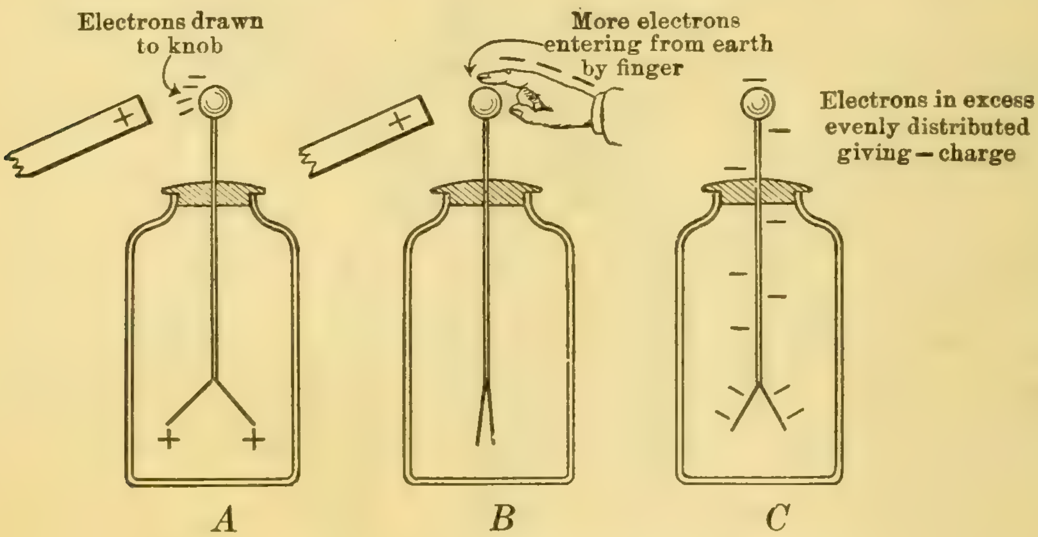


FIGURE 422. — CHARGING AN ELECTROSCOPE.

electrons (−), *which are always present in a conductor*, are attracted upward by the + glass (Figure 422, *A*). This causes some of the atoms in the leaves to be *short of electrons*, that is, to be *positively charged*. Touching the knob with the finger permits electrons from the earth, which is to be regarded as a reservoir of electricity, to flow through the conducting path formed by the body (Figure 422, *B*) and supply the deficiency in the leaves. This causes the leaves to fall together, because the atoms are made neutral, that is, uncharged. The electrons in the knob do not move, because they are held *bound* by the attraction of the + glass rod. When the finger and the + glass rod are removed, there is

now an excess of electrons in the metallic parts of the electroscope and the leaves diverge because of the negative charge that each contains (Figure 422, *C*). The student should work out a similar explanation, with an opposite direction of motion of the electrons, for the process of charging the electroscope positively.

284. The Process of Electrification. — By using the electroscope, we may now investigate the process of electrification carried on in our earlier experiments and seek its explanation by the electron theory.

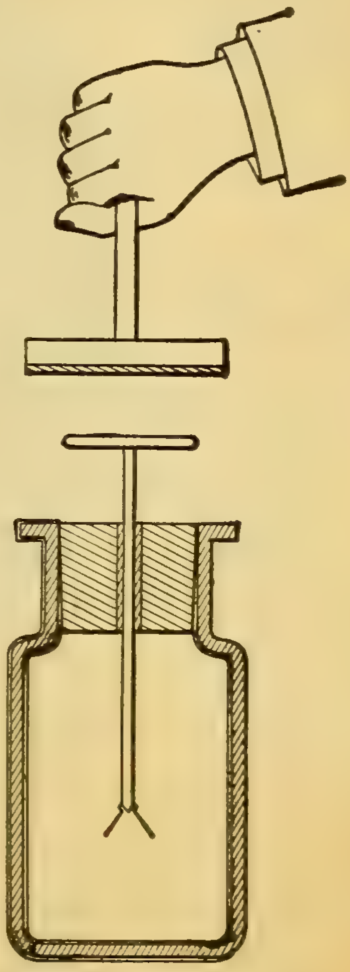


FIGURE 423. — TESTING AN INSULATED PLATE.

EXPERIMENT 110. — Four blocks of wood with hard-rubber handles have each cemented to them one of the following substances: a sheet of glass, a sheet of hard rubber, a piece of silk, a piece of flannel. It is convenient to have two electroscopes, one positively charged and the other negatively. If only one is available, remember that a charge like that of the electroscope will cause a wider divergence of the leaves, while an unlike charge brought near the plate will cause the leaves to approach each other.

Holding the blocks by the insulating handles, rub together the glass and silk surfaces. Then test *both* surfaces for electrification (Figure 423). *Is the silk electrified? With what kind of electricity?* Test in the same way the hard-rubber and flannel surfaces. *Are both electrified? Compare their signs.* If time permits, test all possible combinations of the four plates and state a general conclusion as to what happens when two electrics are rubbed together.

If the above experiment has been carefully performed under favorable atmospheric conditions (that is, in dry air), it will show that both glass and silk, both rubber and flannel, have

been electrified and that in each case the electricity of the cloth was of opposite sign to that of the solid with which it was rubbed. Experiments with a wide range of substances show that when *any two* electrics *are brought into intimate contact and then separated, they are equally and oppositely charged.*

The electron theory furnishes a very simple explanation of this phenomenon of electrification. When the two electrics come in contact, electrons find their way at the points of contact from one material to the other (Figure 424). The material then having the excess of electrons is negatively charged; the one that has lost electrons is positively charged. The rubbing has nothing to do with friction, but is simply a means of bringing more points into contact. A conductor cannot be electrified in this manner for the excess or deficiency of electrons in it will be neutralized by a flow of electrons to or from the earth through the experimenter's body. By holding a conductor with an insulating handle, however, it can be electrified.

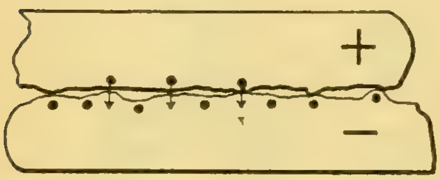


FIGURE 424. — The upper plate is positive, because it has lost electrons (represented by dots) to the lower (negative) plate.

QUESTIONS

1. To what fact do we owe our word "electricity"?

2. How many bodies are necessary to produce electrification? Compare the charges produced on each.

3. What is the simplest way of finding out whether a body is charged?

4. State the effect of like and unlike charges on each other.

5. What is an electron? What is the relation of electrons to atoms?

6. Make a labeled drawing of a gold-leaf electroscope.

Sir Joseph John Thomson (1856–   ). The thing which will be most closely associated with Thomson's name is the Electron Theory, now universally accepted among scientists as an explanation of electrical phenomena. Many men during the last 150 years had aided in developing the idea that electricity exists in small units, now called electrons. Thomson established the theory by a series of fundamental experiments. He is also widely known for his work on the discharge of electricity through gases, conduction by gases, and atmospheric electricity. In 1905, he was appointed professor of Physics in the Royal Institution.

7. Give in order the steps in charging an electroscope by induction.

8. If you have a negatively charged electroscope, state and explain the effect of bringing near it (*a*) a positive charge; (*b*) a negative charge.

9. How and why will an electroscope detect the presence of a charge of electricity on a body brought near it?

10. How can the fact that opposite charges are produced by electrification be proved by an electroscope?

285. Electrostatic Induction. — Just as around a magnet there is a magnetic field, in which magnetic induction takes place, so around an electrified body there is an electric field, in which electric induction takes place. The process of charging an electroscope is an excellent example of *electrostatic induction.*

The attraction of unelectrified bodies by electrified ones also depends on induction. When an uncharged body is brought near a negative charge, some of the electrons in the uncharged body are repelled to the side away from the charged body. On this side a negative charge accumulates, leaving a positive charge on the nearer side (Figure 425). The attraction between the charged body and the unlike charge on the nearer side of the body under induction will always be greater than the repulsion of the two more distant like charges. Hence the two bodies will move toward each other, provided the net attraction between them is greater than the gravitation or friction that tends to keep them separated.

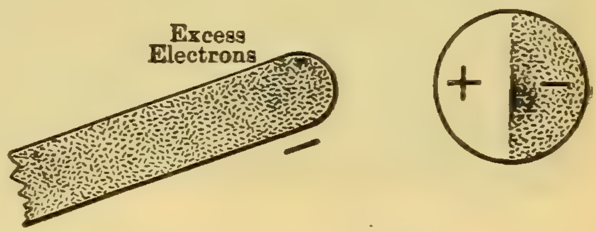


FIGURE 425. — EXCESS ELECTRONS ARE INDICATED BY DOTS.

There are important differences between magnetic and electrostatic induction. In magnetism, the inducing magnet

always has two poles, and the action of both must always be taken into consideration. It is possible, on the other hand, to isolate an electric charge of either positive or negative sign on an insulator or on an insulated conductor, as shown by Experiment 110. This charge of single sign will induce charges of both signs on other bodies in its field, as in charging the electroscope. The charge of the same sign as the inducing charge may always be removed, however, by connecting the body under induction to the earth, as described in the case of the electroscope (§ 283).

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FIGURE 426. — A LIGHTNING FLASH.

The electron stream between cloud and earth produces great heat and the lightning flash.

While a body may have a charge of single sign, the action of induction will always produce an equal charge of opposite sign on surrounding objects. The production of lightning is an important illustration of this principle. The accumulation of the tiny charges of the water droplets that make up a thunder cloud produces a tremendous charge on the cloud as a whole. This charged cloud induces an equal opposite charge on a nearby cloud or on the earth. When the force of attraction between these charges runs up into millions of volts, it is sufficient to set into tremendous motion the

electrons in the intervening air, in spite of the insulating character of the air, and the sudden destructive rush of current that we call *lightning* takes place (Figure 426).

286. Condensers. — An important application of electrostatic induction is found in electric condensers, of which the Leyden jar is a familiar form. The Leyden jar consists of a wide-mouth glass jar, coated within and without with tinfoil for about two thirds of its height (Figure 427). A metallic knob and rod, mounted in an insulating cover, is connected with the inside coating by means of a chain. The jar is charged by *grounding* the outer coating, by holding it in the hand or otherwise connecting it to the earth, and bringing the knob in contact with an electrostatic machine. This machine (Figure 428) is a device by which a constant succession of positive and negative charges may be produced by induction; it is used for experimental work, for medical applications of electricity, and for operating X-ray tubes.

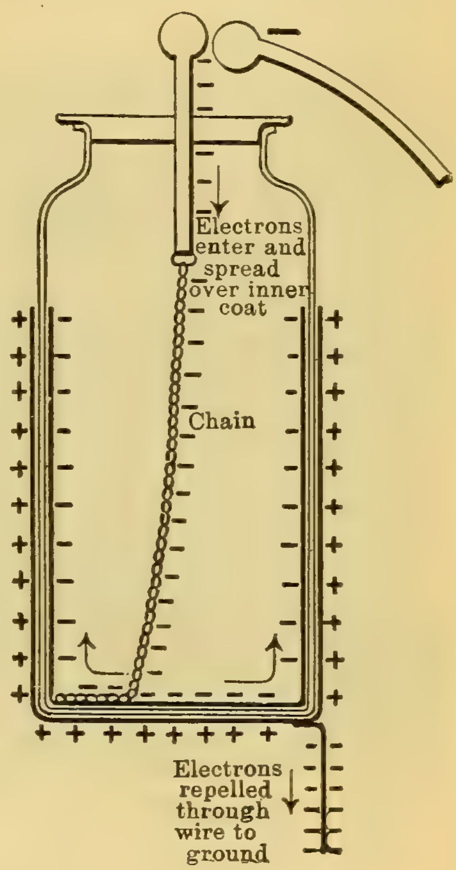


FIGURE 427. — LEYDEN JAR. It is being charged by contact with the — terminal of the static machine.

The action during the charging of the condenser may best be considered in several steps, although all proceed at the same time. Suppose the knob to be connected to the — terminal of the electric machine. Electrons flow from the machine to the inner coating of the jar, accumulating a negative charge there. The inductive action of this negative charge, through the insulating glass of the jar, repels electrons

to the outer side of the outer coating, leaving the inner side of the outer coating deficient in electrons, and therefore positively charged (Figure 429). This positive charge and the negative charge on the inner coating hold each other *bound* by their mutual attraction. But if the outer coating is *grounded* (connected to the earth), the negative electrons on the very outside are repelled to the earth, leaving only the two opposite bound charges on the two coatings. This permits more negative electrons to be added to the inner coating from the machine, for the corresponding electrons on the outer coating do not remain to repel them. The inner and outer surfaces, then, continue accumulating opposite charges until the repulsion of the electrons already present on the inner coating prevent any more from entering it. If now the knob and the outer coating be connected by a conductor, which is carefully insulated to prevent danger to the operator, the two opposite charges will neutralize in a bright, " fat " spark just before the contact is completed, for reasons similar to those given for a lightning flash above.

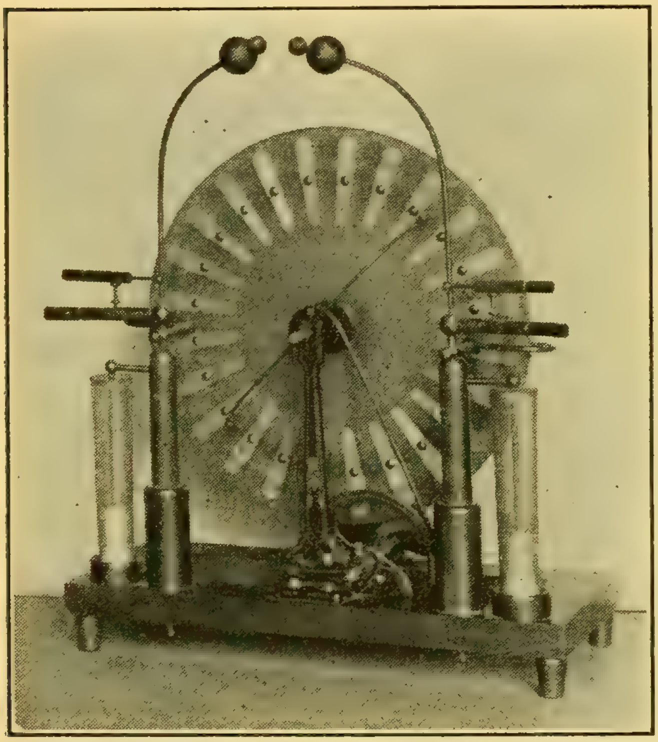


FIGURE 428. — ELECTROSTATIC MACHINE.

Two glass plates, rotating in opposite directions, induce + and − charges, which pass to the terminals above the machine.

Condensers are made in a great variety of form (Figure 428), but always consist of conducting plates separated by

thin layers of insulating material, such as air, glass, or waxed paper. Condensers are said to add "capacity" to the circuit in which they are placed, since on them accumulate greater quantities of + and − electricity than would occur if they were not present. Condensers may be charged by being connected to the terminals of any high-voltage circuit. They find important application in telephone and

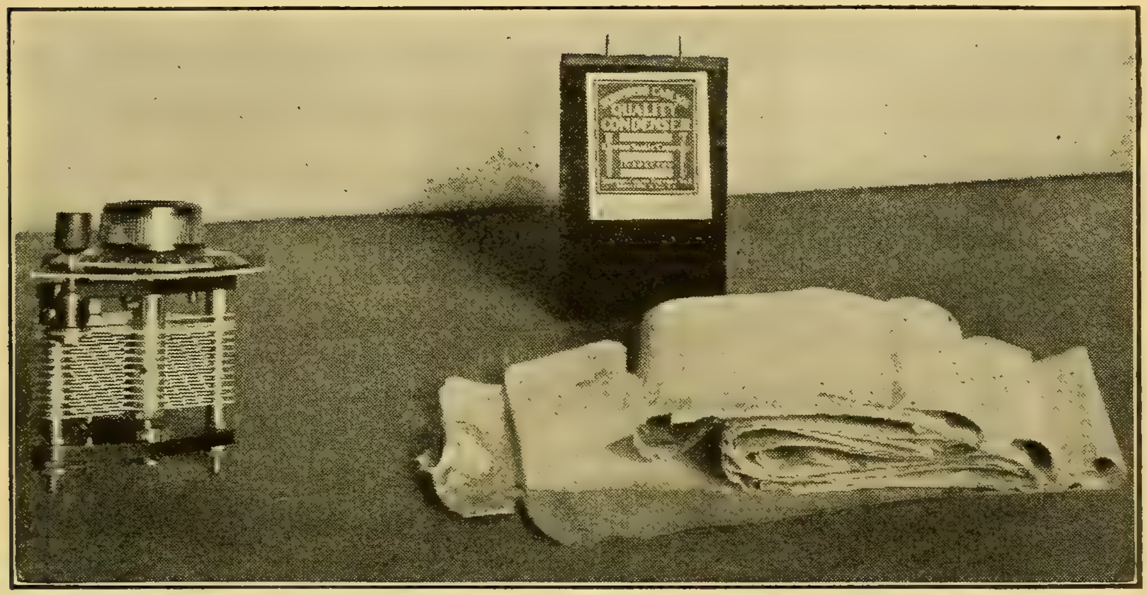


FIGURE 429. — ELECTRIC CONDENSERS.

At the left is a variable air condenser for radio use. In the rear is a telephone condenser made of long strips of tin foil separated by waxed paper, shown in front removed from its case.

wireless circuits, where they serve to neutralize the self-induction (§ 321) of the circuit, and also act as valves or filters, permitting the passage of alternating current and stopping that of direct current, because of the presence of the insulating layer.

There are many other facts and phenomena of static electricity of interest and importance to the advanced student, but lying outside the range of this book.

287. Passage of Electricity through Solid Conductors. — The metals and other conducting solids appear to differ from

insulators in possessing much larger numbers of *free* electrons. Batteries and dynamos *do not add any electricity* to that already present in the conductors forming the circuits to which they are connected. Their action is similar to that of a pump connected to a water-circulating system. The generator constantly furnishes an electromotive force or electric pressure that causes a drift or motion of the electrons in a definite direction, namely, from the negative toward the positive terminal of the generator. It should be noted that this actual motion of the electron stream is in a direction opposite to that usually given as "current direction" — from positive to negative. This is because Franklin's arbitrary selection of positive and negative electricities is just the opposite of what he would have chosen if he had known the recently discovered facts on which the electron theory rests.

An electric current, then, consists of a stream of electrons driven through conductors by electromotive force, actually from negative to positive. This does not change in any way our conception of electromotive force and gives the ampere a still more definite meaning, as the motion of a certain definite number of electrons past a point per second. When part of the circuit consists of a conducting liquid, or of a gas, the mechanism of conduction is somewhat different, as will be shown later; but in these cases also the moving electrons are the essential element in conduction. The fact that good electric conductors are usually also good heat conductors indicates that not only the movement of molecules, but also that of electrons is involved in heat conductivity.

288. Explanation of Molecular Magnets. — The behavior of the molecules of magnetic substances finds ready explanation in the electron theory. Since all atoms contain moving

electrons, we need only assume that many of the electrons in atoms of iron, nickel, etc., are moving in circular orbits around the central nucleus (Figure 430). Such rotating electrons would constitute practically a circular current within the atom. Such a circular current would produce poles in the atom in the same way that the current through a loop of wire produces a N pole on one face of the loop and a S pole on the other. The only difference between this explanation and that given in an earlier chapter is that it treats magnetism as an atomic phenomenon instead of as a molecular one.

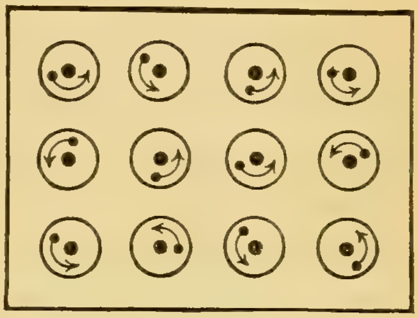


FIGURE 430. — THE END OF A MAGNET.

Each dot is the nucleus of an atom, and the circles are the orbits of rotating electrons.

QUESTIONS

1. Explain what is meant by electrostatic induction.
2. Explain the location of the charges induced on a body.
3. How is lightning produced?
4. Make a labeled drawing of a Leyden jar.
5. Describe in detail the process of charging a condenser.
6. Explain the meaning of "bound" and "grounded."
7. Give uses of condensers.
8. Of what does a current of electricity consist?
9. What is the action of a dynamo in an electric circuit?
10. Describe the structure of the atoms of magnetic substances.

SUMMARY

When two different bodies are brought together and then separated, they are found to be **electrified**. The electric charge on one is **positive**, that on the other is **negative**.

Like charges repel; unlike charges attract. Charged bodies attract uncharged bodies. Electric charges can be retained only by insulators or insulated bodies.

An **electron** is a particle of negative electricity $\frac{1}{1800}$ the mass of a hydrogen atom. In **negative charges** the electrons are in excess. **Atoms** of matter are composed of electrons surrounding a nucleus of positive electricity. A body that is **positively charged** is one that has lost electrons from some of its atoms.

The **gold-leaf electroscope** consists of a rod from which two pieces of gold leaf are suspended. These will repel each other if electrons are either added to or taken away from the gold leaves, since the leaves will then have like charges.

When a charge **like** that of the electroscope is brought near the rod, the leaves will **diverge** more widely. When an **unlike** charge is brought near, the leaves will **fall** toward each other. A charged body brought near an electroscope will cause the leaves to diverge.

During electrification electrons leave one body, charging it positively and pass to the other body, charging it negatively.

When a charged body is brought near an uncharged body, the part of the latter nearer the charged body has a charge of opposite sign **induced** on it, while the more distant part of the uncharged body receives a charge like the inducing charge. This is because the electrons of the uncharged body are attracted or repelled, according to the sign of the inducing charge.

A **condenser** consists of two metallic plates separated by an insulator. When one plate is charged, a charge of unlike sign is induced on the nearer side of the other plate, and a charge of like sign is repelled to the opposite side of the plate. If the plate with the induced charges is connected to the earth, the charge on the outer side is repelled to the ground and the charge on the inner side is held bound. In this way, considerable charges may be caused to accumulate on the two plates of the condenser. If these plates are then connected with a wire, the two charges will neutralize each other by a spark just before contact is completed.

An **electric current** in a wire consists of a stream of electrons driven through the wire from negative to positive by an electromotive force.

Magnetic materials owe their properties to the fact that the electrons in their atoms are rotating around the central nucleus.

EXERCISES

1. Why do bits of paper that have been attracted to an electrified rod suddenly fly off from the rod?

2. Why is a spark sometimes heard when the hair is combed?

3. Leather belts on running machinery sometimes become electrically charged. Explain.

4. Why do not the pulleys over which these belts run show signs of electricity?

5. Explain the difference between a positively and a negatively charged body.

6. "All matter is electricity." Explain this statement.

7. In charging an electroscope, if you touched the knob with the charged body, what kind of charge would the leaves have?

8. Why do the leaves of an electroscope collapse when the knob is touched with the finger?

9. If you did not touch the knob when charging the electroscope, what would happen when you took the charging body away? Why?

10. Why is it dangerous to get too near a highly charged body, even if you do not touch it?

11. In an electrostatic machine the + and − charges accumulate on metal balls. How must these be supported and why?

12. Why is it safe to pick up a Leyden jar by the outer coating, but dangerous to touch the knob at the same time?

13. Why is it wrong to say that we get electricity from a battery?

CHAPTER XXIII

ELECTROCHEMISTRY

289. Liquid Conductors. — When we speak of electrical conductors, we commonly mean copper wires, brass binding posts, carbon brushes, or other pieces of solid conducting material. The manner in which the current is conducted through these solid conductors has already been described (§ 287). Cells or "batteries" contain liquids; to use the earth as a conductor, it is necessary to bury the connections in moist earth. All these facts point to the use of liquids as electrical conductors. Let us then see what are the conditions and methods of conduction in liquids.

290. Electrolytes. — With the exception of mercury and melted metals in which conduction takes place by means of electrons (§ 279), liquids that conduct electricity are generally water solutions. This fact may be verified and various solutions compared by arranging a circuit that includes a source of current, the liquid to be tested, and a detecting instrument, such as a galvanometer or incandescent lamp, all arranged in series.

EXPERIMENT 111. — Arrange the apparatus as shown in Figure 431, and connect the supply wires to the terminals of a 110-volt circuit. Insert the platinum terminals successively into distilled water, alcohol, glycerine, and oil, cleaning them thoroughly after each insertion. If the lamp lights, the liquid must carry the current from electrode to electrode. *Are these liquids conductors?*

Next test solutions of camphor in alcohol, sugar in water, salt solution, dilute sulphuric acid, caustic soda solution. *Which of these are conductors?*

Of all the liquids tested, it will be noticed that only the water solutions of salts, acids, and alkalies conduct the current. The other solutions are insulators (non-conductors). *Substances that conduct electricity when in water solution are known as electrolytes.* Let us see what changes take place in electrolytes before and during the conduction of the current.

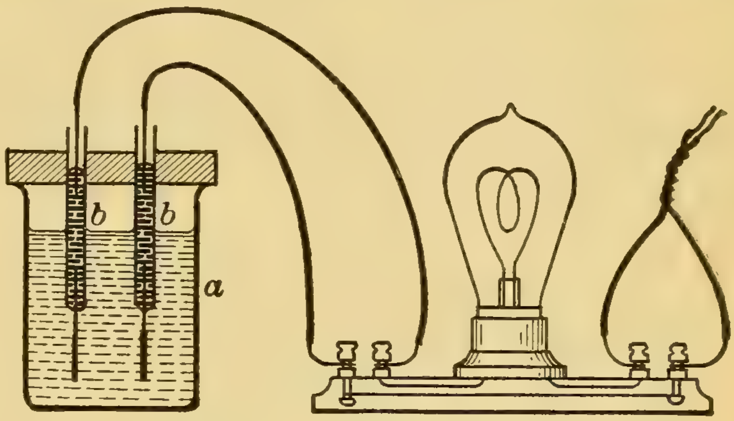


FIGURE 431. — TESTING ELECTROLYTES.

a is a beaker, *b b*, glass tubes filled with mercury and having a platinum wire sealed into the lower end. The lamp is in series with the electrodes.

291. Dissociation. — Molecules of common salt (sodium chloride) consist of atoms of sodium and of chlorine. When salt is dissolved in water, an action takes place in its molecules similar to that which occurs when the glass rod and the silk (§ 277) are separated after being brought together. The act of solution separates or *dissociates* many of the sodium chloride molecules, each molecule yielding a negatively charged chlorine atom and a positively charged sodium atom (Figure 432). These charged atoms are known respectively as chlorine *ions* (−) and sodium *ions* (+). Another way of saying the same thing is that when a sodium chloride molecule dissociates, the chlorine ion takes an electron from the

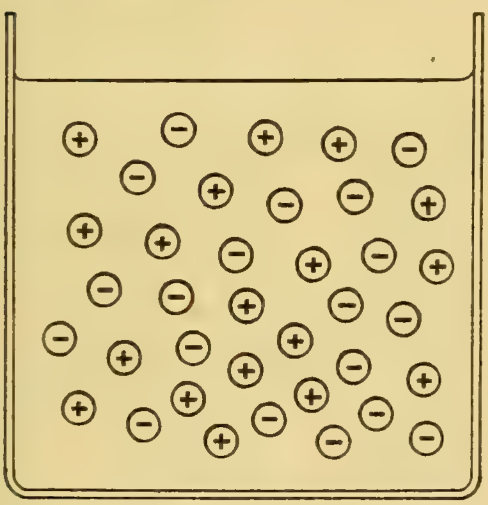


FIGURE 432.—A SALT SOLUTION.

The + sodium ions and the − chlorine ions are moving at random in all directions.

sodium, becoming negatively charged and leaving the sodium positively charged. A similar dissociation takes place *during the solution of every electrolyte.* The following table gives the names and chemical formulas of the electrolytes most important in electrochemical work, with the ions into which they dissociate.

TABLE OF ELECTROLYTES

NAME	FORMULA	+ ION	− ION
Sulphuric acid	H_2SO_4	H^+H^+ (hydrogen)	SO_4^{--} (sulphion)
Sodium hydroxide	$NaOH$	Na^+ (sodium)	OH^- (hydroxyl)
Copper sulphate	$CuSO_4$	Cu^{++} (copper)	SO_4^{--} (sulphion)
Ammonium chloride	NH_4Cl	NH_4^+ (ammonium)	Cl^- (chlorion)

292. Behavior of Ions in Solution. — When an electrolyte dissociates, the solution contains great and equal numbers of positive and negative ions, freely moving about in the water. As these positive and negative ions come within range of one another, they are continually recombining, because of the attraction between their charges, and then again dissociating. Since the + and − ions are present in equal numbers, there is no external evidence that the liquid is electrically charged. If, however, two oppositely charged bodies, like the terminals of the electric circuit in Experiment 111, are introduced into the solution, the negative ions are repelled by the negatively charged − terminal and attracted by the + terminal. The action on the + ions is just the reverse. The net result is the establishment of two distinct drifts or currents of ions: − ions to the + terminal and + ions to the − terminal (Figure 433). *It is by means of these definitely moving streams of ions that the electric current is conducted through the liquid.*

Thus the circuit was completed and the current passed constantly through the lamp, causing it to light.

293. Electrolysis. — As each − ion reaches the positive electrode or *anode,* it loses an electron (its "negative charge") to the terminal and becomes electrically neutral. The + ion gains an electron at the negative electrode, *cathode,* and becomes electrically neutral. The result is an increased concentration at the electrodes of the element or elements present in the two kinds of ions at the anode and cathode respectively. A metallic element is likely to be deposited on the − electrode, while a non-metal usually escapes as a gas, unless some secondary chemical reaction takes place. *The permanent separation of an electrolyte into its constituents by the passage of an electric current is called electrolysis.*

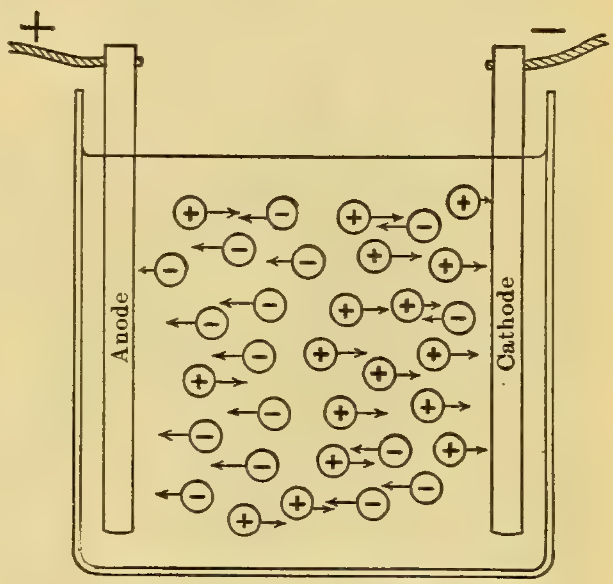


FIGURE 433. — ELECTROLYSIS.

The charged anode and cathode give the ions definite direction, − ions to the anode and + ions to the cathode.

In giving the explanation of an electrolysis, it should be remembered that *the electric current is not the cause of the dissociation into charged particles, but simply determines the direction in which they move. The dissociation takes place during the act of dissolving and has occurred before the electrodes are inserted.*

294. Electrolysis of Water. — We have already seen that distilled water is practically an insulator. If, however, a small amount of an electrolyte is added to the water, it becomes

possible to separate the water into its constituent parts by electrolysis. A little sulphuric acid is commonly employed and the apparatus shown in Figure 434 is convenient for the collection of the hydrogen and the oxygen liberated from the water. The chemical action is as follows: The ions present in the solution are H^+ and $SO_4{}^{--}$. During the electrolysis, (1) the H^+ ions drift to the cathode, (2) there lose their charge and (3) the resulting H atoms unite to form molecules and finally (4) bubbles of hydrogen gas. This gas displaces the water in the tube and collects therein. The gas is identified as hydrogen by its behavior when a burning splinter is applied to it.

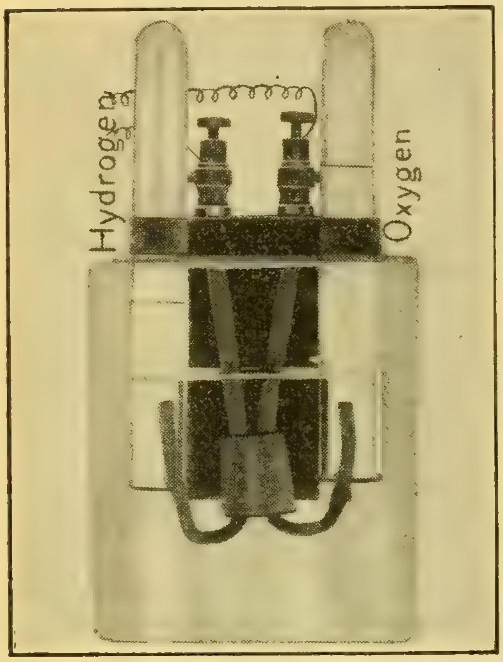


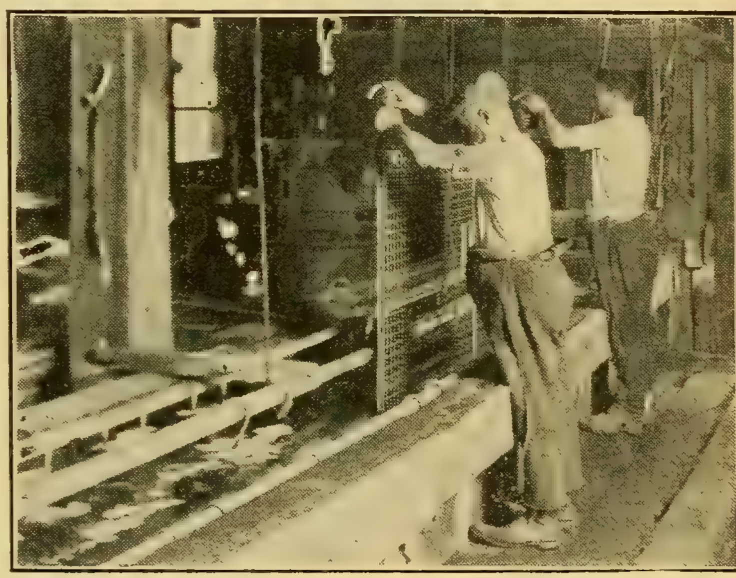
FIGURE 434. — The electric current liberates oxygen at the anode and hydrogen at the cathode.

When the $SO_4{}^{--}$ ions reach the anode and lose their charges, a secondary chemical action takes place, the SO_4 reacts with water, forming sulphuric acid and liberating oxygen. The oxygen bubbles rise into the tube. Thus at the end of the process, there will be as much sulphuric acid as at the beginning, so this process is properly an electrolysis of water.

Electrolysis is employed commercially to produce pure hydrogen and oxygen. It will be noticed that the volume of *hydrogen* produced is *twice* that of the oxygen. Advantage is taken of this fact to test the polarity of the terminals of a circuit. There are enough dissolved salts present in ordinary water to make it an electrolyte. So, when the terminals are

dipped into water, the more rapid stream of bubbles rising will be the hydrogen and will indicate that the pole from which they are rising is the cathode or − terminal.

295. Electroplating. — There are many practical applications of electrolysis, most of which are studied in chemistry. Electroplating, however, is so important that every student of physics should understand the elements of the process (Figure 435). A typical case may be illustrated by an experiment.



© *Ewing Galloway.*

FIGURE 435. — ELECTROPLATING.

A metal grating to be plated is being lowered into a nickel solution, and will be suspended from the negative center rod.

EXPERIMENT 112. — Into a rectangular battery jar pour a solution of copper sulphate. In this place a sheet of copper and a sheet of lead. Connect the copper to the + terminal and the lead to the − terminal of a battery or other source of current capable of producing a pressure of 3 to 6 volts. In a short time a red coating of copper will appear on the lead, and if the process continues the lead will be heavily copper plated, and the copper plate will be noticeably thinner.

The action in this case is very similar to the electrolysis of water. When the + ions reach the cathode and lose their charge, since they are copper instead of hydrogen, they are deposited there and form the plating. Each SO_4^{--} ion, reaching the copper plate, loses its charge and unites with an atom of copper, forming a new molecule of copper sulphate. This molecule then dissociates and the process continues. There is a constant transfer of copper

from the copper anode through the cell to the cathode. Other salts of copper, such as the cyanide, are frequently used.

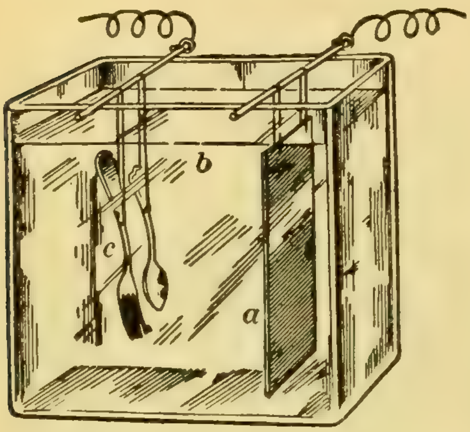


FIGURE 436. — SILVER PLATING.

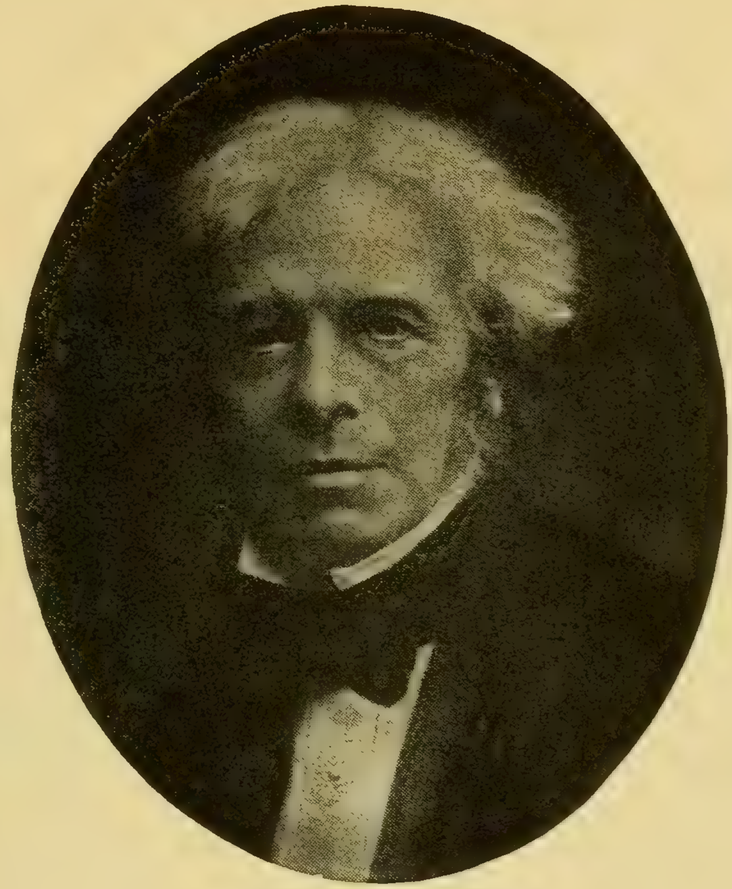
a is the silver anode, *b*, the electrolyte of silver cyanide, and *c*, the articles to be plated.

Electroplating can be carried out with a variety of metals, such as nickel, silver, and gold (Figure 436). In each case, the anode is a slab of the plating metal and the cathode is the article to be plated. The electrolytes usually employed in the cases mentioned are nickel ammonium sulphate, and silver and gold cyanides. It is even possible for bedsteads and other articles to be plated with brass, by using brass anodes and an electrolyte containing salts of copper and zinc in the proper proportions in the electrolyte.

Copper is refined by using an impure copper as an anode and a sheet of pure copper as the cathode in a solution of copper sulphate (Figure 437). The pure metal is plated on the cathode and the impurities fall to the bottom as mud.

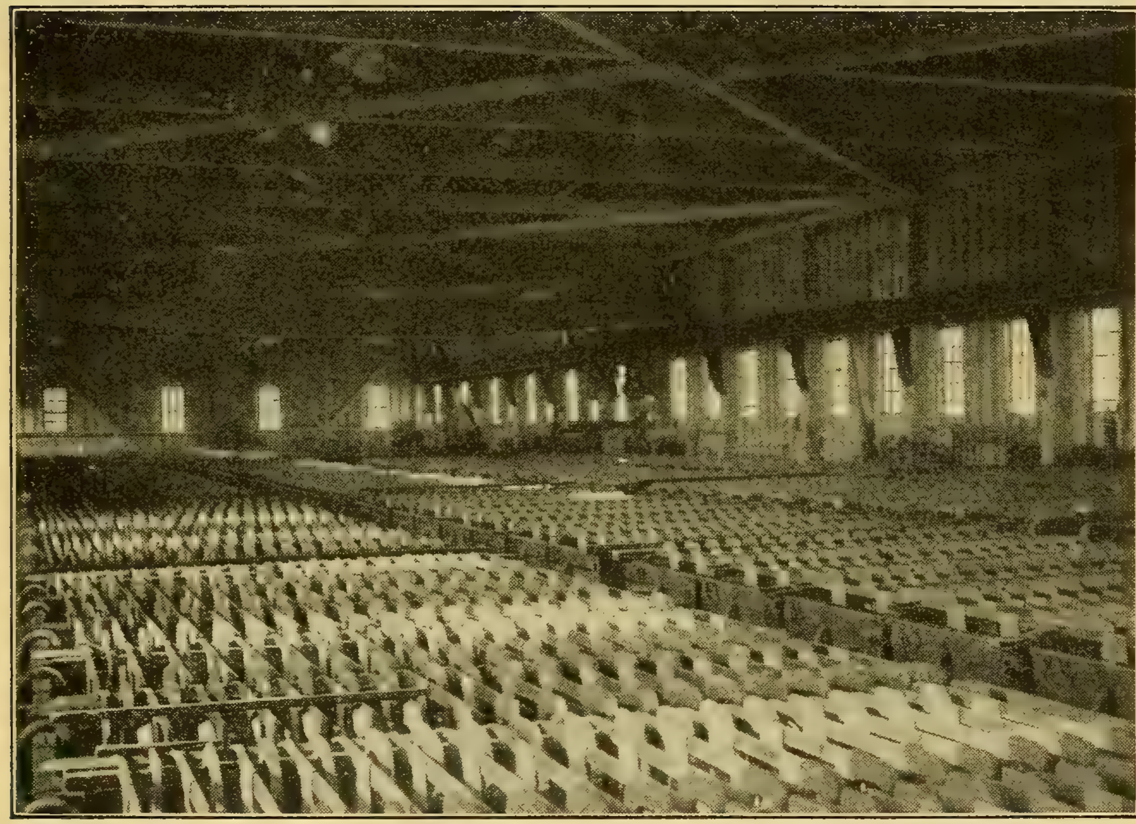
296. Electrotyping. — This is a special case of electroplating of considerable interest and importance. Its chief use is in the preparation of the plates from which books are printed, although it is often used to copy medals and other art objects.

In making book electrotypes, the type is set up, corrected, and the various cuts inserted in the proper place on the page (Figure 438, left). The entire page, as assembled, is then pressed into a sheet of special wax, so that an impression or mold is made (Figure 438, center). The surface of this mold is then thoroughly covered with fine graphite, in order to make it an electric conductor. This prepared wax



Michael Faraday (1791–1867) began his scientific work as an assistant to Sir Humphry Davy in the Royal Institution. Here he spent the remainder of his life as an assistant, director, and professor. This lifetime of intensive work produced results of enormous value to science. Faraday's most important work was along electrical lines. He caused a current-bearing wire to rotate continuously around a magnet (motor principle); predicted and proved the production of currents by induction (generator and transformer principle); set forth the laws of electrolysis; and forecast the electromagnetic theory of light.

is made the cathode in a copper-plating bath, and the current controlled so that the copper will be deposited slowly. This gives a very fine deposit, that follows every detail of the impression. The plating is continued until a deposit of the thickness of a visiting card is secured. This is thick enough to stand removal from the wax. Melted lead or



Courtesy of Scientific American.

FIGURE 437. — The current carries the pure copper from the impure anodes to the cathode plates of pure copper. Other metals, including gold and silver, fall to the bottom of the tanks. The pairs of plates in each tank are connected in parallel.

type metal is poured into the back of the copper plate to strengthen it further. When this backing is hard, it is planed smooth to proper thickness for the press (Figure 438, right). Thus a printing block is secured that will print an entire page, and that has a surface hard enough to allow hundreds of thousands of impressions to be made, whereas ordinary type would soon become worn and indistinct.

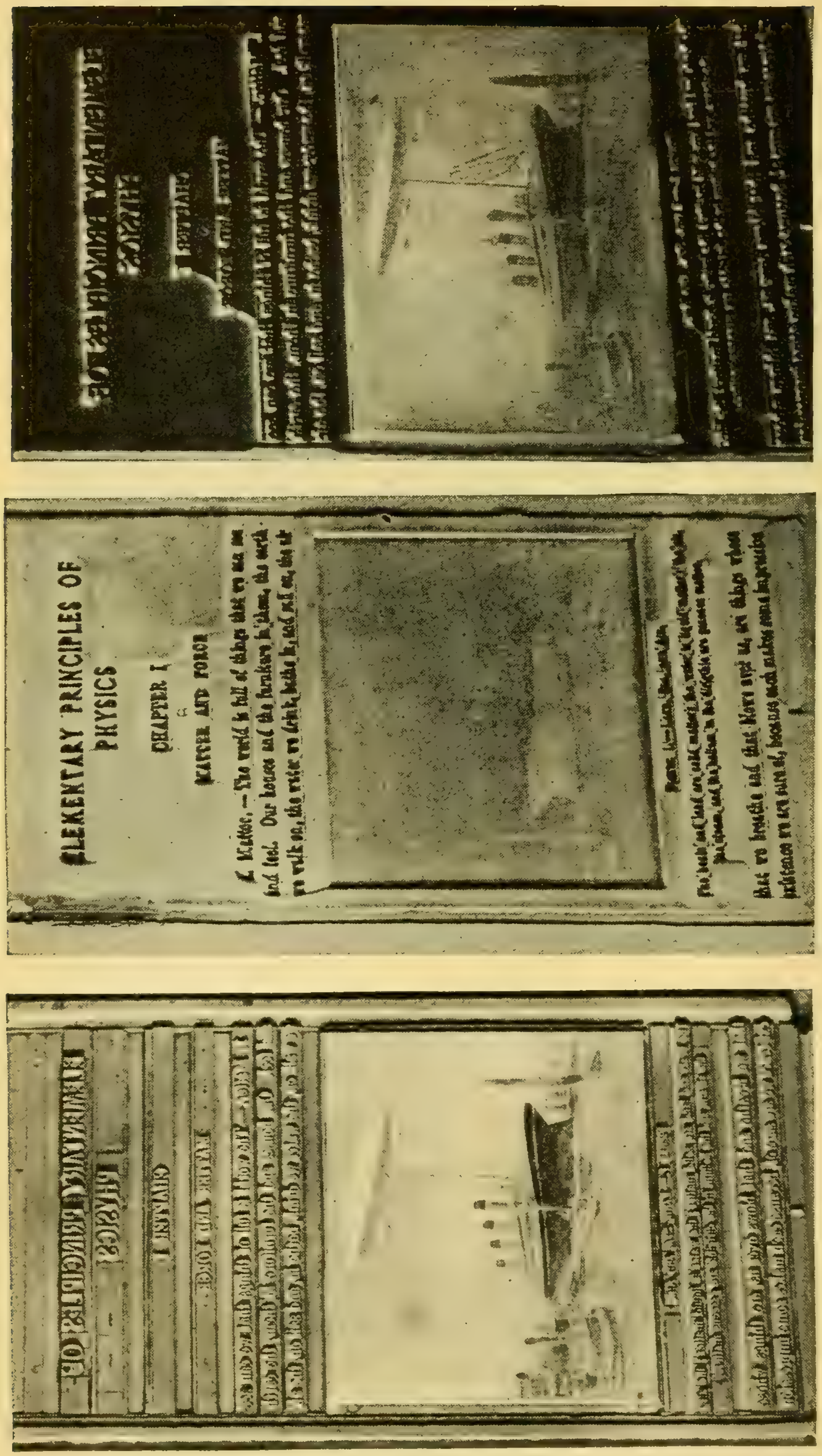


FIGURE 438. — ELECTROTYPING.

The picture at the left shows the type set up. The mold formed by pressing this into the wax is shown in the center. At the right is the finished electrotype.

297. Electrolysis of Pipes. — Dangerous leaks and much damage is often caused by electrolysis in water and gas pipes buried in the earth. In most electrical power houses one terminal of the generator is "grounded" or connected to the earth. In electric railway systems, the outgoing current flows through the trolley wire or third rail, which is carefully insulated. The return current, however, is through the

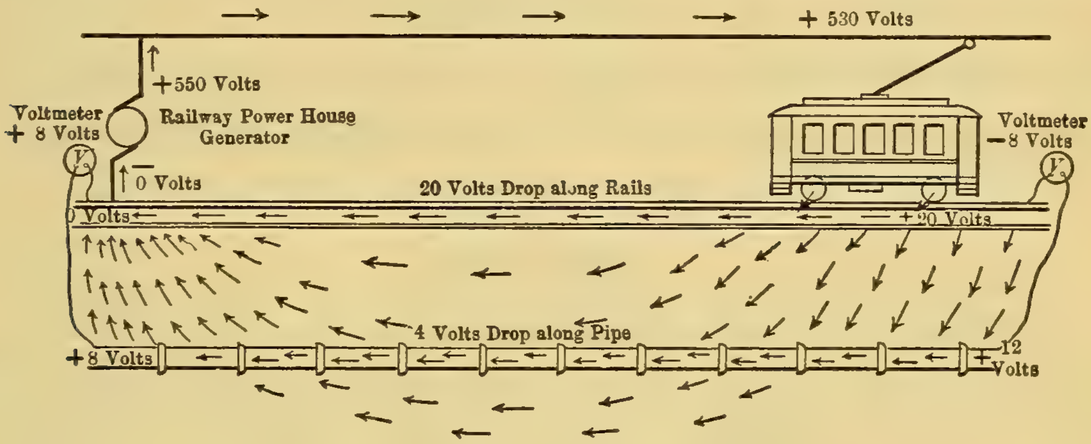


FIGURE 439. — ELECTROLYSIS OF PIPE, ACCORDING TO GANZ.
Arrows show general path of current through the ground, toward the pipe near the car and from it near the power house.

rails and the earth itself (Figure 439). Now moist earth is a fair conductor, but iron or lead pipes are much better conductors. So a large part of the return current is likely to take its way along pipes running in the general direction of the power house. That is, the current strays into the pipe near the place where it leaves the electric car, and leaves the pipe near the power house, to continue through the moist earth. Soil water is an electrolyte, generally somewhat acid. We have then the equivalent of two electrolytic cells — one between the track and the pipe and the other between the pipe and the power house. In the first case (track — pipe) the pipe acts as a cathode, hydrogen or a metal is deposited at the pipe, and no damage is done. In the second case (pipe — power house) the pipe is the anode and the

negative ion of the soil water electrolyte is likely to combine with the metal of the pipe, gradually eating the pipe away until a hole is made. This action is similar to that of the metallic anode in electroplating.

The means of preventing this pipe electrolysis is to secure as good a metallic return circuit for the current as possible. This is expensive and is therefore unfortunately often neglected, with the disastrous consequences referred to above. A similar destructive electrolysis is apt to occur when there is a loose joint in an electric circuit exposed to moisture.

SUMMARY

Electrolytes are substances whose solutions conduct electricity. The molecules of such substances **dissociate during solution** into positively and negatively charged **ions.** Current is conducted through electrolytes by these ions moving between the terminals immersed in the solution. The **anode** is the **positive** terminal of an electrolytic cell and the **cathode** is the **negative** terminal.

Electrolysis is the permanent separation of an electrolyte into its constituents by the passage of an electric current.

Distilled water is practically non-conducting. When a little sulphuric acid is added to water and an electric current passed through, the final products are oxygen at the anode and hydrogen at the cathode. The total amount of sulphuric acid remains unchanged.

An object is **electroplated** by making it the cathode in an electrolytic solution containing a salt of the metal with which the object is to be plated. The anode is made of the plating metal.

An **electrotype** is made by coating a wax mold of the type or article to be copied with graphite, and making this the cathode in a copper-plating bath. When a sufficiently thick plating has been obtained, this plating is removed and given a strong backing of

lead. Electrotypes are mounted on wood blocks and used in printing books.

Electrolysis of metal pipes buried in the earth results from the return along the pipe of currents that stray from electric railways. When they leave the pipes to return to the grounded negative of the power house, the action of negative ions from soil acids disintegrates the pipe.

EXERCISES

1. What is an electrolyte? What classes of chemical compounds are electrolytes?

2. When does the dissociation of these chemical compounds take place?

3. Name three electrolytes and state the ions into which they dissociate.

4. What difference is there in the behavior of the ions of an electrolyte before and after the terminals of an electric circuit are introduced into it?

5. Describe how an electric current is conducted by an electrolyte.

6. Define *electrolysis; anode; cathode.*

7. Which terminal of an electrolytic cell is marked +?

8. Why is the presence of sulphuric acid or some similar substance necessary in the electrolysis of water? Is the water or the sulphuric acid permanently separated into its constituents?

9. With the aid of a diagram, describe in detail the electrolysis of water. State the proportions of hydrogen and oxygen obtained.

10. Describe how you would electroplate a brass spoon with silver.

11. In electroplating, how is the strength of the solution maintained?

12. Describe the manufacture of an electrotype.

13. Explain why electrotype plates are used in printing books.

14. Describe how copper is purified by electrolysis.

15. Make a sketch of a power house, railroad system, and underground pipes, showing the path of current that will cause electrolysis of the pipes.

16. State where electrolysis of the pipe occurs and explain why.

17. State one means of preventing electrolysis of pipes.

Alessandro Volta (1745–1827), while professor of physics at Como, Italy, became famous for his experiments in static electricity. Volta developed from his experiments the "voltaic" cell whose action is known to be due to two metals and an electrolyte. This discovery enabled scientists to produce currents of electricity. Practically the whole science of current electricity dates back to Volta's discovery. Volta's explanation of the electrical pressure of the cell is commonly accepted to-day.

CHAPTER XXIV

VOLTAIC CELLS

THE discovery that the energy of a chemical reaction could be utilized to maintain a continuous flow of electric charges, that is, an electric current, was made by the Italian scientist Volta shortly before 1800. His "electric pile" consisted of alternate pieces of zinc and silver, separated by pieces of cloth wet with salt water (Figure 440). This was the first electric battery.

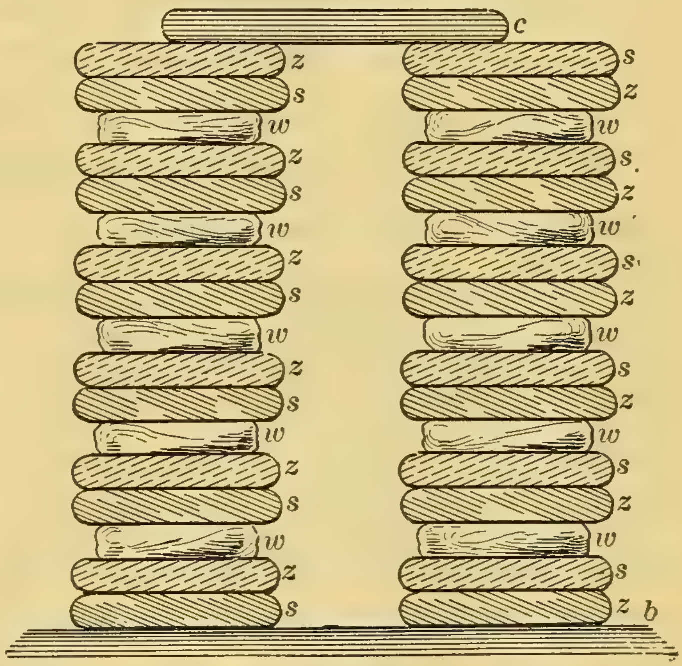


FIGURE 440. — VOLTA'S PILE.

Zinc disks, *z*; silver disks, *s*; cloth pads wet with salt water, *w*. The bottom zinc and silver disks are the terminals.

298. Simple Voltaic Cell. — A jar of dilute sulphuric acid, in which are dipped a zinc plate and a copper plate, is a *simple cell* (Figure 441). In the electrolyte, sulphuric acid, there are present the ions H^+, H^+, and $SO_4{}^{--}$. When a metal is placed in water, there is a tendency for its atoms to enter the solution as ions. This tendency is much greater in the case of zinc than it is in the case of copper. When zinc is immersed in dilute sulphuric acid, Zn^{++} ions enter the solution. The

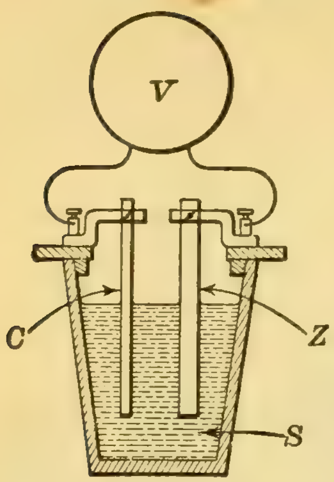


FIGURE 441.—SIMPLE CELL.

Copper, *C*; zinc, *Z*; dilute sulphuric acid, *S*.

Zn^{++} ions are positive because each has left behind on the zinc plate two electrons (−). This accumulation of electrons constitutes a negative charge on the zinc plate (Figure 442). The Zn^{++} ions, on entering the solution, repel the H^+ ions that are already present. In the simple cell, these H^+ ions are repelled in the direction of the copper plate. As in electrolysis (§ 294), the H^+ ions, reaching the copper plate, take electrons from it and become atoms. The loss of electrons to the hydrogen leaves the copper plate with a positive charge.

The chemical action in the cell results, then, in leaving too many electrons on the zinc plate and too few on the copper. The overcrowded electrons on the zinc plate try to push each other off the plate, and this push, together with the attraction of the + plate, is the electromotive force of the cell. If the plates are now connected by a wire, the electromotive force will cause an electric current to flow through the wire, in an attempt to equalize this difference in charge. Thus the cell acts as an electric pump, producing a continuous flow of electrons (an electric current) in any conductor

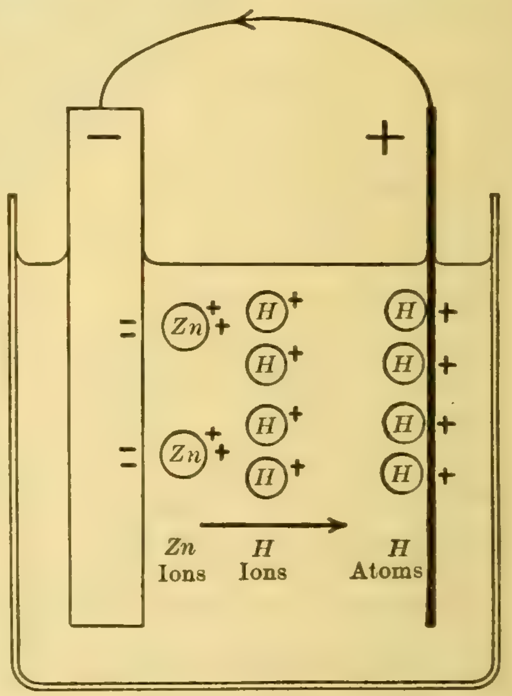


FIGURE 442.—ACTION IN A SIMPLE CELL.

Zinc ions, entering the solution, repel the hydrogen ions to the copper, where they lose their charge.

by which its plates are joined. Following the naming in common use, the copper terminal is the + terminal of the cell, and the zinc the − terminal.

299. Polarization. —

EXPERIMENT 113. — Connect the terminals of a simple cell to a resistance of about 20 ohms, having a switch in the circuit. Across the cell terminals place a low-reading voltmeter. With the switch open, read the voltmeter. Close the switch, and observe any *continuous* change that occurs in the voltmeter reading.

The drop in voltage, that occurs after the current has been flowing for some time, is due to *polarization* of the cell. The cause of this polarization is the accumulation on the positive (copper) plate of these hydrogen bubbles which have not yet escaped (Figure 443). This accumulated hydrogen reduces both voltage and current: (1) The hydrogen tends to set up an electromotive force in a direction opposite to that of the cell, and thus decreases the effective electromotive force. (2) The hydrogen reduces the conducting area of the plate, and so increases the resistance.

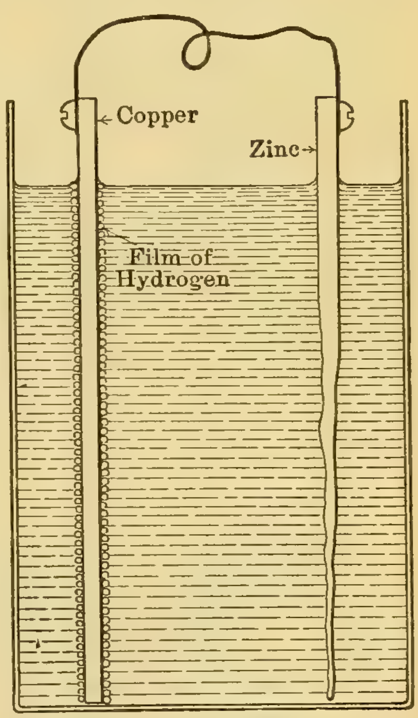


FIGURE 443. — POLARIZATION.

The hydrogen film checks the current, and sets up an electromotive force in the opposite direction.

The *remedy* for polarization is either to prevent the hydrogen from reaching the copper plate or to remove the hydrogen by causing it to combine with oxygen. The first remedy is applied in the Daniell cell (§ 301) and the second in the Leclanché cell (§ 302). Because of the rapid polarization of the simple cell, it is not used for practical purposes.

300. Local Action. — When commercial zinc is used in a cell there is a waste of material and energy that takes place, even when the cell is not in use. This waste is caused by *local action.*

Experiment 114. — Set up a simple cell with commercial (impure) zinc, and carefully observe the plates, when the circuit is open. *At which place is there a free formation of bubbles?*

Remove the zinc plate, and rub a little mercury over its surface. Replace the "amalgamated" zinc plate in the solution, and observe whether bubbles of hydrogen are now liberated at the zinc plate.

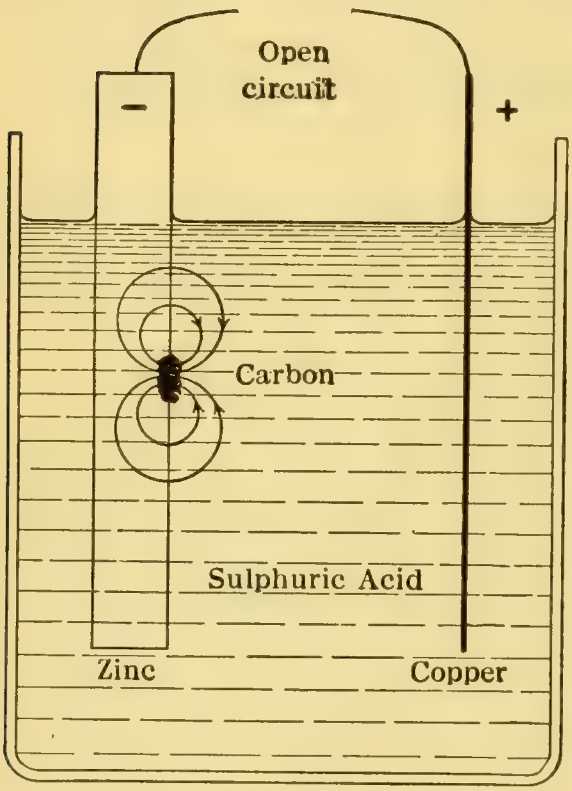


Figure 444. — Local Action.

The carbon particle sets up a small cell with the zinc, wasting the zinc without contributing current to the external circuit.

The cause of local action is the particles of impurities, such as iron and carbon, that are found in the surface of the plate. Each foreign particle acts on a small scale like the copper plate of the cell, hydrogen ions being repelled to it by the zinc ions that enter the solution (Figure 444). As the particles are imbedded in the electrically conducting zinc, a small local circuit is set up for each of them and the zinc wastes away as long as it is immersed in the acid, whether the cell is delivering current to an external circuit or not. The mercury amalgamates with the zinc, and apparently covers over the impurities, while it constantly brings to the surface the pure zinc, since this dissolves in the mercury. Hence in practical cells, amalgamated zinc is used as the negative plate.

301. Daniell Cell. — This is an early form of cell, designed to *prevent* polarization. In this cell, the copper is surrounded with a solution of copper sulphate. This solution is kept separate from the sulphuric acid by placing the zinc and sulphuric acid in a cup of unglazed porous porcelain, while the copper is immersed in the copper sulphate solution contained in the outer vessel (Figure 445). In the *gravity cell* (Figure 446), the two liquids are separated by the difference in their specific gravity. In either form of cell, Cu^{++} ions are repelled to the copper plate instead of H^+ ions. This copper is deposited on the copper plate, simply adding to its weight without changing its character. So no polarization will take place as long as the supply of copper sulphate is maintained. Such cells are used in "closed-circuit" work, such as the local battery in telegraph lines.

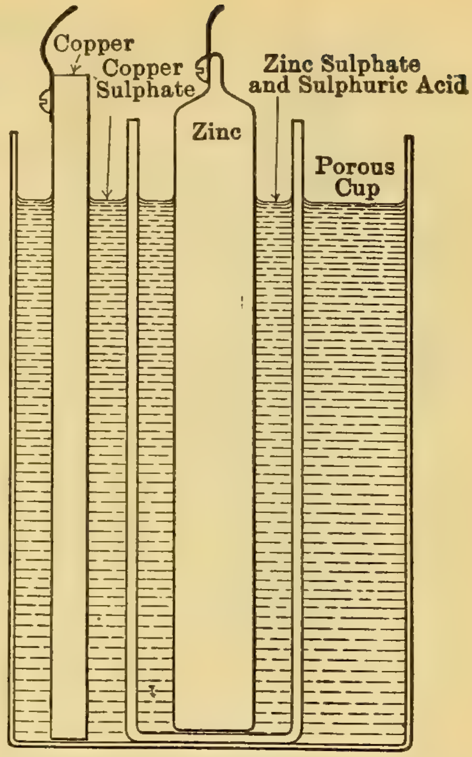


FIGURE 445. — DANIELL CELL.

Zinc in zinc sulphate and copper in copper sulphate are separated by a porous cup, which prevents the liquids from mixing, but permits current to go through.

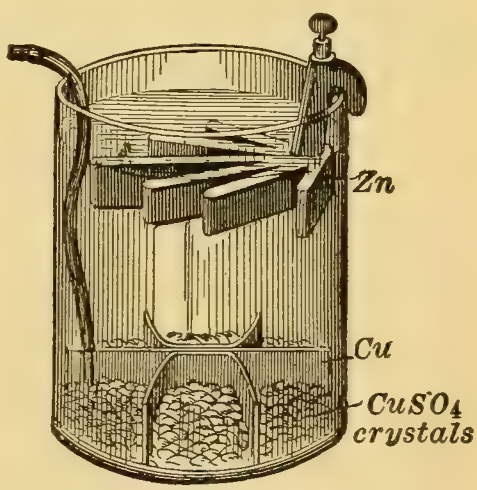


FIGURE 446. — GRAVITY CELL.

Zinc sulphate is lighter than copper sulphate. The crystals keep the latter solution saturated.

302. Leclanché Cell. — The electrodes in this cell (Figure 447) are zinc and carbon, and the electrolyte is ammonium chloride (sal ammoniac). The chemical action

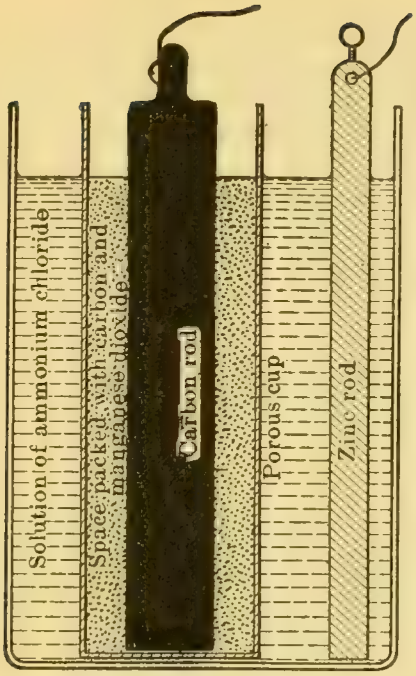


FIGURE 447. — LECLANCHÉ CELL.

The mixture in the porous cup depolarizes the carbon.

is more complicated than in the simple cell, and ammonia gas and hydrogen gas are liberated at the + carbon plate. The ammonia largely dissolves in the water, but the hydrogen gradually polarizes the cell. In order to depolarize the cell, the carbon rod forming the + plate is usually packed in a mixture of manganese dioxide and granulated carbon. The polarizing hydrogen gradually combines with oxygen from the manganese dioxide, and as the cell stands for some time after it has been used, this action depolarizes it. As this action proceeds slowly, the cell is only suitable for intermittent action, like the ringing of door bells. In other words, it is an " open-circuit " cell.

303. Dry Cells. — The dry cell, a modified form of the Leclanché cell, is used more than any other. The zinc of the dry cell (Figure 448) is in the form of a can, which serves as a container for the other parts. The zinc can (*Z*) is lined with absorbent paper, which is saturated with sal ammoniac solution. The carbon rod (*C*) is placed in the center of the cell, and the space between it and the can is filled with a mixture of manganese dioxide and granulated carbon, thoroughly wet with sal ammoniac, zinc chloride, and other chemicals. The completed cell

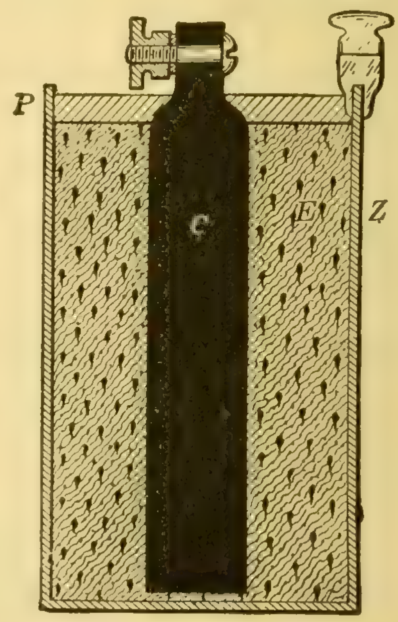


FIGURE 448. — DRY CELL

is sealed as shown at (P) to prevent the evaporation of the liquid. The dry cell is more compact than the other cells described. As it has no liquid to spill, it can be carried in any position, as, for instance, in a flashlight. The use of these cells for door bells, radio sets, and a great variety of other purposes is too familiar to need further mention.

Dry cells are permanently injured by short-circuiting them, and by causing them to deliver larger quantities of current than they are designed for. Dealers frequently test dry cells by short-circuiting them through an ammeter. This practice is very likely to injure the cell and gives no sure indication of the current output of the cell on an ordinary circuit. Dry cells also deteriorate rapidly with age, even when not used. When a dry cell fails to act further, it may be replaced cheaply, or it may be made to serve some time longer by punching holes through the zinc and placing the whole cell in a jar containing sal ammoniac solution.

QUESTIONS

1. What are the parts of a simple cell?

2. Name the ions in the electrolyte and explain in detail their action during the operation of the simple cell.

3. With the aid of a diagram, explain what happens when a cell is polarized.

4. State remedies for polarization and name cells in which they are employed.

5. With the aid of a diagram, describe local action in a cell.

6. State, with reason, the remedy for local action.

7. Make labeled diagrams of the Daniell and gravity cells.

8. What is the use of the porous cup in the Daniell cell?

9. Explain how polarization is prevented in the Daniell and gravity cells.

10. Why is the gravity cell called a *closed-circuit* cell?

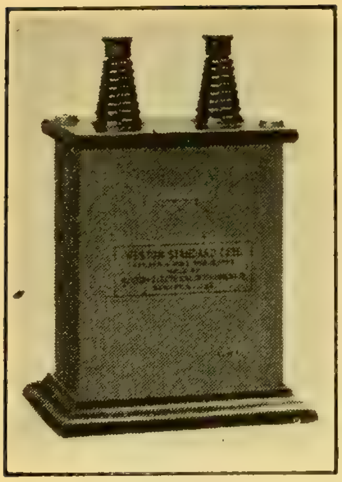


FIGURE 449. — WESTON CELL.

11. Describe the Leclanché cell and explain its action.

12. Make a labeled diagram of a dry cell and state the use of each material.

13. For what purposes are dry cells adapted and why?

14. Give directions concerning the selection and use of dry cells.

304. Voltage and Current Relations in Cells. — The voltage of a cell is entirely independent of its size, and depends only on the materials of which it is made. A simple cell or a Daniell cell furnishes a pressure of approximately 1.1 volts; Leclanché and dry cells, 1.5 volts. The Weston cell (Figures 449, 450), when made according to accurately standardized directions, is so definite in voltage that it is used as a standard for testing voltage.

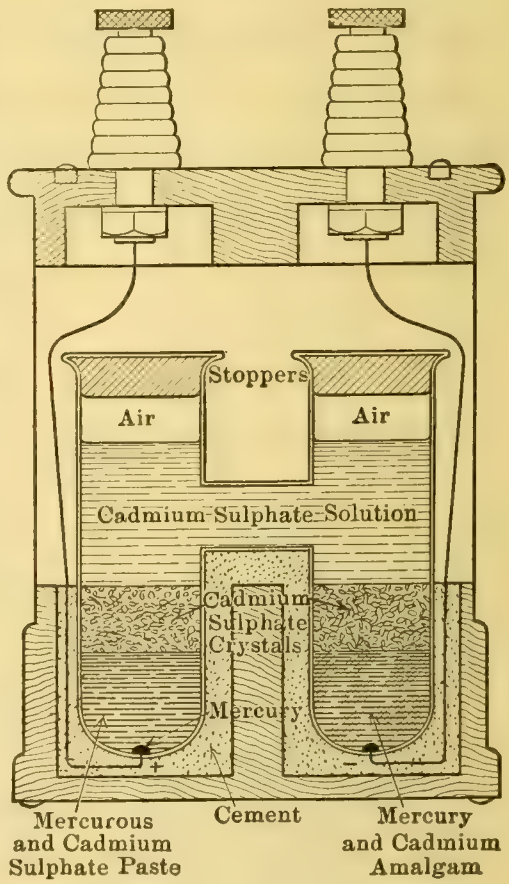


FIGURE 450. — SECTION OF WESTON CELL.

This cell is used for testing purposes only, never with less than 10,000 ohms in series with it. Its voltage is 1.0183 at 20° C.

The maximum current that a cell can furnish through a very low resistance (short circuit) depends on the internal resistance of the cell, for some of the pressure developed must be used in sending the current through the cell itself. The chief resistance of the cell is in the electrolyte. Hence the larger the cross section of the electrolyte between the plates and the shorter the

distance between the plates, the less the resistance (§ 252), and therefore the larger the current that it will permit to flow through the external circuit. In other words, the larger the cell, the larger the current that it will furnish. A flashlight dry cell will give far less current than the size used for bells, etc., because the resistance of the flashlight cell is much greater. At the same time, the fact that a larger cell has a greater supply of chemically active materials enables it to maintain the current in any circuit for a greater time than a small cell.

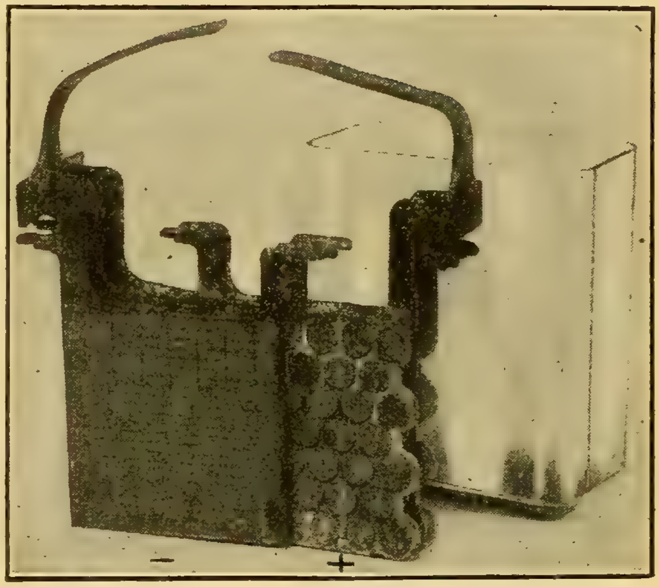


FIGURE 451. — LEAD STORAGE CELL.

The positive and negative plates are shown partly separated, with the containing jar behind. Thin sheets of wood or perforated rubber are placed between the + and − plates.

305. Storage Cells. — Zinc, which is the active plate in most important primary cells, is consumed in the production of the current, and the frequent replacement of the zinc makes these cells an expensive source of current. In the secondary or *storage* cells, the active plate is a compound which gives up one of its elements to the electrolyte when the cell is furnishing current (*discharging*), and later has this element restored to it by having a current passed through it from another source (*charging*).

The lead storage cell is the most familiar type (Figure 451). The positive plate consists of a framework or grid of lead, in the spaces of which lead peroxide (PbO_2) is packed. The negative plate is another grid of lead, with its pockets packed

with finely divided or *spongy* lead. The electrolyte is dilute sulphuric acid. When the cell is furnishing current (discharging) the following chemical reaction takes place:

$$\underset{\substack{\text{lead}\\ -\text{ plate}}}{Pb} + \underset{\substack{\text{lead oxide}\\ +\text{ plate}}}{PbO_2} + \underset{\substack{\text{sulphuric acid}\\ \text{electrolyte}}}{2\,H_2SO_4} \longrightarrow \underset{\substack{\text{lead sulphate}\\ \text{both plates}}}{2\,PbSO_4} + \underset{\text{water}}{2\,H_2O}$$

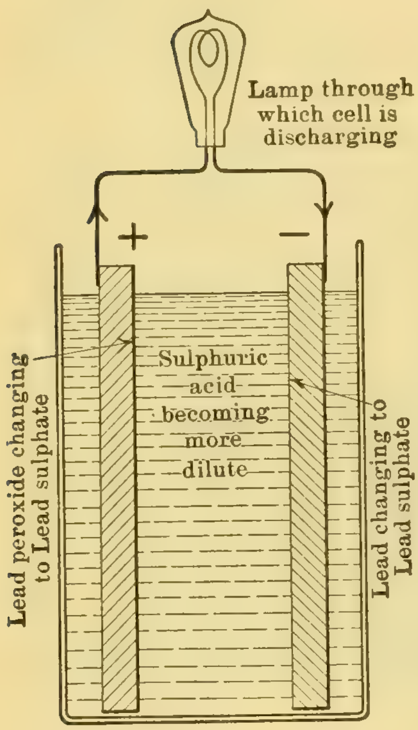


FIGURE 452. — ACTION IN STORAGE CELL FURNISHING CURRENT.

That is, each of the plates tends to become coated on the surface with lead sulphate (Figure 452). As this action proceeds, the electromotive force of the cell remains about 2 volts for a considerable time, and then gradually diminishes, because the plates are becoming alike.

The cell must then be *charged* by connecting it to some other electric generator that will send a current through it. This current causes electrolysis and the final result is the reversal of the action given above, so that the equation for charging is:

$$\underset{\substack{\text{lead sulphate}\\ \text{both plates}}}{2\,PbSO_4} + \underset{\text{water}}{2\,H_2O} \longrightarrow \underset{\substack{\text{lead}\\ -\text{ plate}}}{Pb} + \underset{\substack{\text{lead oxide}\\ +\text{ plate}}}{PbO_2} + \underset{\substack{\text{sulphuric acid}\\ \text{electrolyte}}}{2\,H_2SO_4}$$

The chemical changes in charging the storage cell are shown in Figure 453. Charging and discharging may be repeated a great number of times before the gradual disintegration of the plates makes it necessary to replace them. As considerable amounts of hydrogen and oxygen are given off during the process of charging, it is necessary to add water frequently. Only distilled water should be used, as water

containing any dissolved salts would be likely to set up local action with the impurities that would be deposited on the plates during charging.

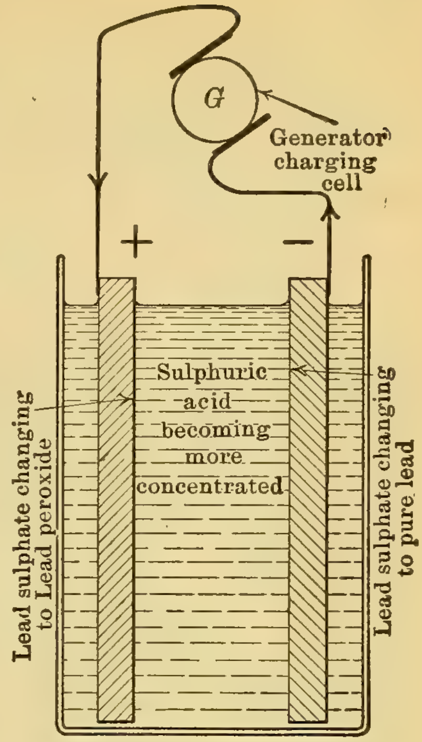


FIGURE 453. — ACTION IN STORAGE CELL BEING CHARGED.

306. The Edison Storage Cell. — In this cell both plates are of nickel-plated steel (Figure 454), with the active material contained in perforated pockets. In the positive plate, when the cell is charged, the active material is nickel peroxide and in the negative plate it is finely divided iron. The electrolyte is potassium hydroxide. During discharge, the iron is oxidized and the nickel peroxide is partly reduced. When the cell is charged, the iron oxide is reduced to iron and the nickel peroxide is formed again. This cell is much lighter and stronger for the same capacity than the lead cell, and it suffers less from misuse and neglect. On the other hand, the first cost of the Edison cell is much greater and it yields a less proportion of the energy used in charging. Its pressure is about 1.2 volts.

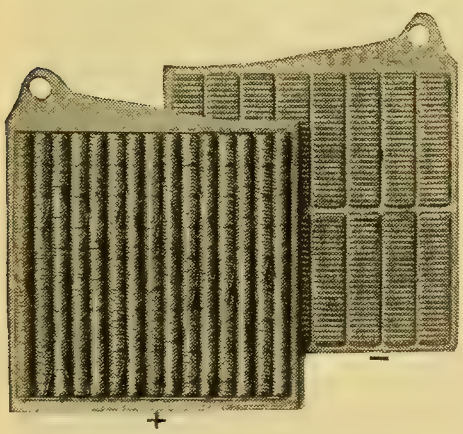


FIGURE 454. — PLATES OF EDISON STORAGE CELL.

307. Use of Storage Cells. — The most familiar use of the storage cell, chiefly of the lead type, is for automobile starting, lighting, and ignition. The batteries employed consist of either three or six cells connected in series, giving 6 and 12 volts respec-

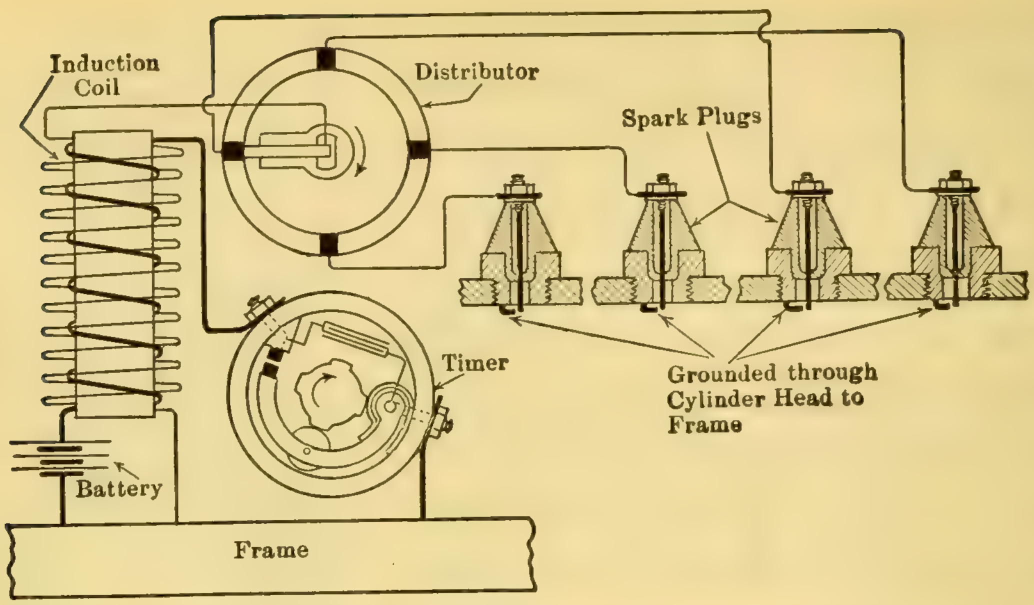
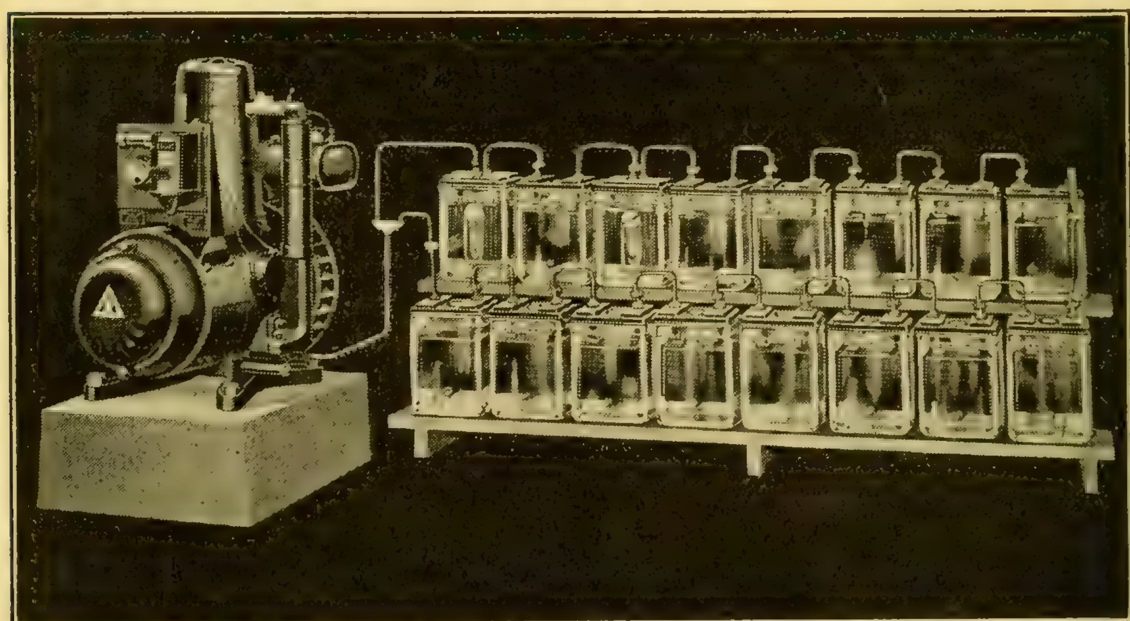


FIGURE 455. — AUTOMOBILE IGNITION SYSTEM.

By means of the induction coil a spark is produced in one of the spark plugs every time the circuit is broken by the timer. The distributor connects the proper spark plug each time.

tively. In ordinary use these cells are kept charged by a generator driven by the engine of the car. Current from this battery is used to operate the self-starter, a motor which



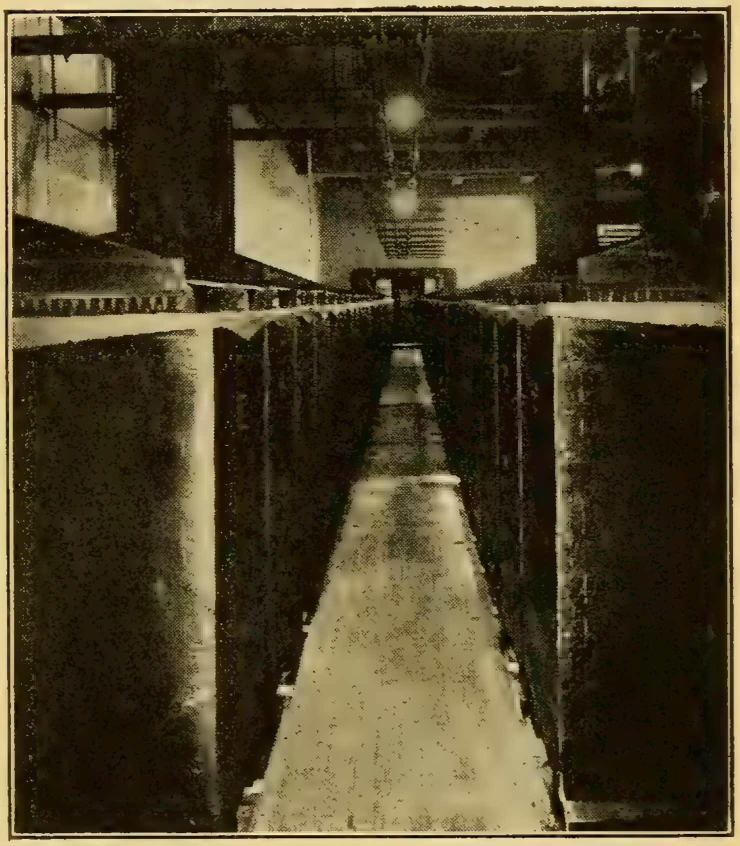
Courtesy Delco Light Co.

FIGURE 456. — LIGHTING PLANT FOR COUNTRY HOUSE.

This consists of gas engine, generator, and storage battery.

cranks the car at starting. This same battery furnishes current for ignition (Figure 455) and for lighting the lamps, when the engine is stopped or running slowly. Electric vehicles also use storage batteries as a source of motive power. Storage batteries, kept charged by a generator geared to the axle, light railway coaches.

Another important use of storage cells is for lighting buildings in the country, far from a central power station (Figure 456). These batteries are charged by a gas-engine-driven generator, running a few hours during the daytime, and not only furnish light for the house, but also power for small machinery. Large power stations use huge storage batteries (Figure 457) to help when the load on the station is heavy and as an emergency source of current for the fields of the dynamos. This battery is connected in parallel with the generators (Figure 458), so as to be charged when the demand on the station is small. Storage cells are widely used in radio sets, particularly for the filament battery (§ 484). They are extensively used in telephone systems.



Courtesy New York Edison Co.

FIGURE 457. — STORAGE BATTERY ROOM OF LARGE POWER PLANT.

The weight of lead storage batteries and the mechanical

weakness of their plates has considerably restricted their use. In all storage cells during discharge chemical energy is being converted into electrical energy; this chemical energy must be restored to the cell during the process of recharging. Not all the electrical energy used in charging the cell is converted into chemical energy: part of it is dissipated as heat. It is well to remember, therefore, that it takes longer to charge

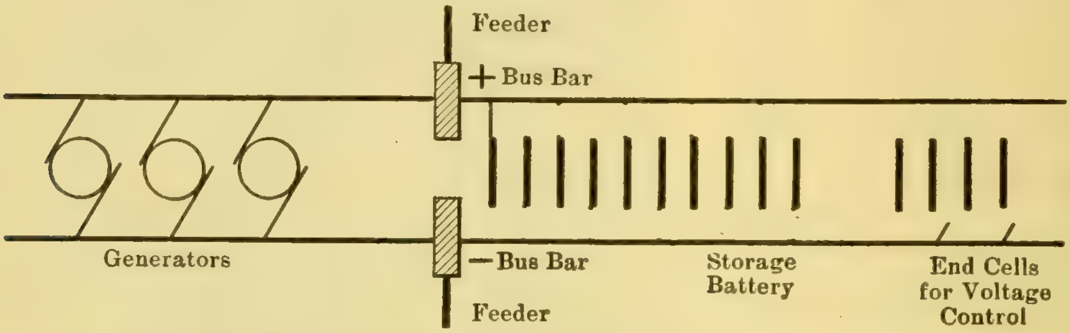


FIGURE 458. — POWER HOUSE BATTERY CONNECTION.

The proper voltage is secured by connecting the cells in series, and voltage drop provided for by using more end cells. The entire battery is in parallel with the generator. A similar connection is used in an automobile battery.

a storage cell than it does to discharge it, if the rate of current flow is the same in both cases. This, again, limits the use of the storage cell to intermittent service. The storage cell, used unintelligently, is likely to be a fruitful source of annoyance and dissatisfaction.

308. Grouping of Cells. — The voltage of a single cell is too small for most purposes, so in practice cells are connected to form *batteries.* The use to which the battery is to be put determines whether the cells are to be connected in series, or in parallel. The *series* connection is the more common, because this gives a greater voltage to send current through the external resistance. In the series connection (Figure 459), the positive of one cell is connected to the negative of the next, and so on through the battery. The voltage at the

battery terminals is, then, the combined voltage of the cells. If the cells are all alike, this will be the voltage of one cell multiplied by the number of cells. A battery of 6 dry cells, each having a voltage of 1.5 volts, will be 6×1.5 volts = 9 volts. Since all of the current flows through each cell, the internal resistance of the battery is the resistance of one cell multiplied by the number of cells. If each of the dry cells just mentioned has an internal resistance of 0.075 ohm, the internal resistance of the battery will be 6×0.075 ohm = 0.45 ohm. If this battery is now connected to a 5-ohm circuit, the total resistance will be $5 + 0.45 = 5.45$ ohms. Applying Ohm's Law, the current through the circuit will be

$$I = \frac{E}{R} = \frac{9}{5.45} = 1.67 \text{ amperes}$$

If we let e = E.M.F. of one cell, r = internal resistance of one cell, R = the external resistance, and n = the number of cells, then the Ohm's Law formula for the series grouping may be written:

$$\mathbf{I = \frac{ne}{nr + R}}$$

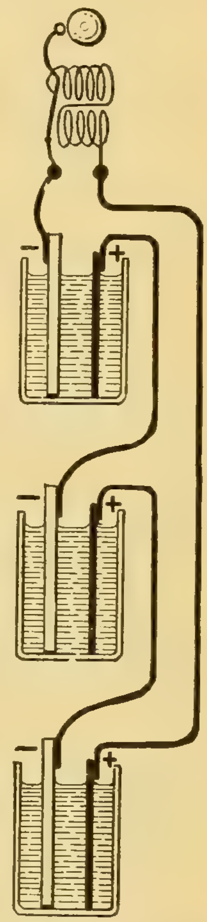


FIGURE 459. — CELLS IN SERIES.

Increased voltage.

It is only when the external resistance is *exceedingly small* that cells are connected in *parallel*. In that case, the important thing is to reduce the internal resistance of the battery, and all the positive plates are connected to one battery terminal and all the negative plates to the other (Figure 460). This has the effect of making the battery act like a single

cell with greatly enlarged plates (§ 304). The voltage of the battery will be the voltage of one cell. The internal resistance will be the resistance of one cell divided by the number of cells. If the six cells mentioned in the preceding paragraph

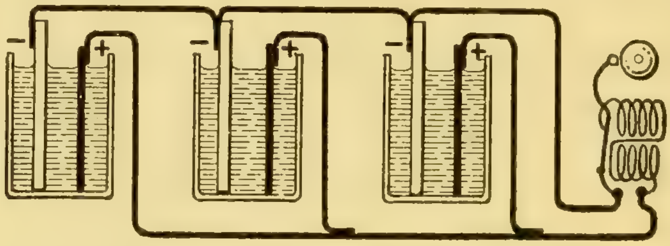


FIGURE 460. — CELLS IN PARALLEL.
Decreased resistance.

are connected in parallel, the E.M.F. of the battery so formed will be 1.5 volts — the voltage of one cell. The internal resistance will be $\frac{0.075}{6} = 0.0125$ ohm. If this battery is connected to an external circuit having a resistance of 0.01 ohm, the current flowing will be $\frac{1.5}{.01 + 0.0125} = 66.6$ amperes. Such a grouping is very unlikely in practice, as this current from a battery of dry cells would ruin the cells in a very short time. Using the same symbols as in the case of the series grouping, the formula for the current from a parallel battery will be:

$$I = \frac{e}{\frac{r}{n} + R}$$

QUESTIONS

1. Upon what does the voltage of a voltaic cell depend? Give the voltage of each cell described in this chapter.

2. How does the size and distance between the plates of a cell affect the current that it will furnish? Explain.

3. What is the advantage of storage cells over primary cells?

4. Make labeled diagrams showing (*a*) the parts of a storage cell; (*b*) a fully charged storage cell furnishing current; (*c*) a discharged storage cell being charged. In each case, show the direction of the current.

5. Is the + terminal of a storage cell the same during charge and discharge? Explain.

6. Why must water be periodically added to storage cells? Why should distilled water be used?

7. Give the chemical changes during the charging and discharging of a lead storage cell.

8. Name the essential parts of an Edison storage cell.

9. What is the change in this cell during discharge?

10. Do local action and polarization occur in storage cells?

11. Does a storage cell store electrical energy or chemical energy? Explain.

12. State four uses to which storage cells are particularly adapted and explain why they are preferred to primary cells in these uses.

13. When should cells be connected in series and when should they be connected in parallel?

14. Five cells, each having an E.M.F. of 1.5 volts and an internal resistance of 0.1 ohm, are connected in series through a resistance of 2 ohms. Find the current produced.

15. The same cells are connected in parallel to the same resistance. Find the current.

16. Six cells, each having an E.M.F. of 2 volts and an internal resistance of 0.5 ohm, are to be used with an external resistance of 0.1 ohm. Find the current (*a*) when they are connected in series; (*b*) when they are connected in parallel.

SUMMARY

A **simple voltaic cell** consists of sulphuric acid in which are dipped a zinc plate and a copper plate. Zinc + ions, entering the solution, leave an excess of electrons on the zinc plate. The zinc + ions repel hydrogen + ions already present in the solution. These + ions give their charges to the copper plates. If the two plates are joined by a wire, a current of electricity will

flow through the wire. A voltaic cell produces an electromotive force.

Polarization results from the accumulation of hydrogen on the positive plate. This (1) increases the resistance of the cell; (2) sets up an opposing electromotive force. The **remedy** for polarization is to prevent the hydrogen from reaching the copper plate, or to remove it after it has been deposited. Both are accomplished by chemical action.

Local action is due to small local circuits established between impurities in the zinc plate and the plate itself. The **remedy** is to amalgamate or coat the zinc plate with mercury.

In the **Daniell and gravity cells**, the copper plate is kept surrounded with copper sulphate. Copper instead of hydrogen is deposited on the copper plate and polarization is prevented. This cell has constant voltage and is used in closed-circuit work. Its pressure is about 1.1 volts.

The **Leclanché cell** has zinc and carbon electrodes and ammonium chloride as an electrolyte. The carbon is packed in manganese dioxide and granular carbon. Oxygen from the dioxide unites with the hydrogen on the plate and so depolarizes the cell. This cell is used for open-circuit work, such as door bells. Its voltage is about 1.5.

The **dry cell** has the same electrodes as the Leclanché cell, separated by a paste of carbon and manganese dioxide, wet with ammonium chloride, zinc chloride, and other chemicals. The action and voltage is the same as the Leclanché cell. This is the most convenient form of cell.

The **voltage** of cells is independent of the size and distance of the plates. The larger and the nearer the plates, the less the internal resistance of the cell and the larger the amount of **current** it will furnish.

The **lead storage cell** has, when charged, a positive lead peroxide plate and a negative lead plate. The electrolyte is dilute sulphuric acid. During **discharge** (furnishing current), both

plates become somewhat coated with lead sulphate. The cell is **charged** again by passing in a direct current at the positive plate and out at the negative. Electrolysis takes place, and the plates are changed to lead peroxide and lead again. The voltage when charged is 2.

The **Edison storage cell** uses nickel peroxide for the positive plate and iron for the negative. The electrolyte is potassium hydroxide. The voltage is 1.2.

Storage cells are used in automobiles, radio sets, and as a reserve source of electric power.

Cells are **connected in series** when the **external resistance is high** and **in parallel** when it is **very low**. In series, the electromotive force of the battery is equal to that of one cell multiplied by the number of cells, and the internal resistance is the product of the resistance per cell by the number of cells. In parallel, the E.M.F. is that of a single cell and the internal resistance of the battery is that of one cell divided by the number of cells.

Series	Parallel
$I = \dfrac{ne}{nr + R}$	$I = \dfrac{e}{\dfrac{r}{n} + R}$

EXERCISES

1. Make a comparative table of the simple, Daniell, Leclanché and dry cells under the following headings: Name; positive plate; negative plate; electrolyte; depolarizer; voltage; uses.

2. Explain how the zinc plate of a cell secures a – charge.

3. Explain why a current *continues* to flow through a wire connecting the plates of a cell.

4. Make four drawings to show the formation of hydrogen bubbles at positive and negative poles when a simple cell with unamalgamated zinc is used on (1) open and (2) closed circuit,

and when amalgamated zinc is used on (3) open and (4) closed circuit.

5. Why are simple cells not used outside physical laboratories?

6. Are the materials of a cell and its energy wasted as a result of polarization? Explain.

7. How does local action cause a waste of material?

8. Which needs more frequent renewal in primary cells, the positive or the negative plate? Explain.

9. Why are dry cells not adapted to telegraph circuits, in which the circuit is closed a large part of the time?

10. Why should a dealer not order a year's supply of dry cells delivered at a time?

11. Comment on the practice of testing dry cells with an ammeter.

12. Explain fully how you would construct a storage cell, and how you would go about making it produce current.

13. When and why are storage cells better than primary cells?

14. Lead sulphate is a non-conductor of electricity. What would be the effect on a storage cell of continuing the discharge until the plates were entirely covered with lead sulphate?

15. State the relative advantages and disadvantages of lead and Edison storage cells.

16. Discuss the advantages and disadvantages of storage cells for operating automobiles.

Joseph Henry (1799–1878) ranks as one of the foremost of American scientists. When first noticed, he was an instructor in Albany Academy, where his experiments with lifting magnets of great power attracted much attention. These experiments were the forerunners of the telegraph and the relay. He discovered the principle of induction in parallel circuits before Faraday did, but did not publish this until after Faraday had done so.

He became professor of Natural Philosophy at Princeton and later the director of the Smithsonian Institution. While holding these positions he aided the development of almost every branch of natural science.

CHAPTER XXV

ELECTROMAGNETIC INDUCTION

Electricity has become the silent servant of the civilized world. The first method of producing electricity by the consumption of zinc in a voltaic cell was too expensive to permit a widespread use of electrical energy. A cheap means of producing this form of energy on a large scale was required to widen the scope of usefulness of what had been heretofore a scientific curiosity. This cheaper and more practical method of production was found, and to-day nearly all of the electrical energy used comes from a process called *electromagnetic induction.*

309. Discovery of Induction. — The credit for discovering this means of producing electricity is generally given jointly to the British scientist, Faraday, and to the American, Henry. Oersted and Ampère had already made known their discovery that electric currents caused magnetic fields. It had also been shown that a pivoted magnet was deflected when placed near a current-bearing wire. Faraday himself had shown that a current-bearing wire could be kept continually moving about a magnet pole. The way was clear for Faraday and Henry, independently, first to infer and then to prove experimentally that this operation could be reversed; *that a wire moved in a magnetic field so as to cut across the lines of force would have a current set up in it.* Upon this fundamental principle is based the production of the

great quantity of electrical energy that does so many things for us to-day.

Experiment 115. — Attach the ends of a long flexible wire to the terminals of a sensitive galvanometer. Move a straight section of the wire across the pole of a powerful electromagnet. *Does the galvanometer indicate the presence of a current?* Reverse the direction of motion of the wire in the field. *Does the current direction reverse?* Move the wire *along* instead of *across* the lines of force. *Result?* Move the wire *slowly* across the field. *Result?* Wind a portion of the wire into several turns and thrust this coil quickly over one of the magnet poles. *Compare the amount of current with the previous cases.* Thrust the coil over the opposite pole and note the direction of deflection of the galvanometer.

A current flows in a wire only because there is an electromotive force applied to the wire. The size, duration, and direction of the current indicated by the galvanometer are simply indications of the size, duration, and extent of an E.M.F. induced within the wire when it moved across the magnetic field. We may learn from this experiment (1) that an induced E.M.F. appears in a wire when the wire is moved *across* a magnetic field, (2) that the direction of this E.M.F. depends upon the direction of magnetic flux and the direction of motion of the wire in the field, (3) that the size of the E.M.F. depends upon the number of lines of force cut per second. The number of lines cut per second depends upon the speed of motion of the wires through the field × number of lines in the magnetic field × number of wires acting together in cutting the lines of force. (4) The E.M.F. is induced only so long as the wire is moving across the magnetic field.

310. Fleming's Rule. — The relations involved in (2) above are stated in Fleming's rule for the determination of the direction of an induced E.M.F. when the directions of the

flux and of the motion of the conductor is known. Let the thumb, forefinger, and center finger of the right hand be held at right angles to each other. Now if the hand is held so that the thumb points in the direction of the motion of the wire, and the forefinger in the direction of the magnetic field (from N to S), then the center finger will indicate the direction of the induced E.M.F. or of the current resulting from it (Figure 461).

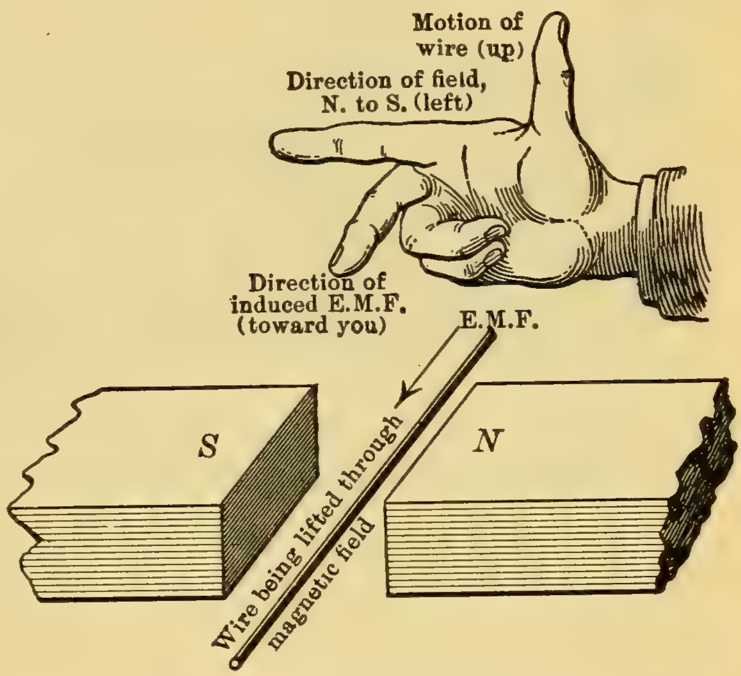


FIGURE 461. — APPLYING FLEMING'S RULE.

311. Electric Generators. — We have seen that *an E.M.F. is induced whenever a wire is moved across a magnetic field.* An electromagnetic generator, commonly called a dynamo, is a device for producing electrical pressure by moving conductors continuously through a magnetic field. A simple form of generator would be a rectangular loop of wire mounted so as to turn between the poles of a U-shaped magnet. By providing this loop with an outlet for current, we can determine the characteristics of the E.M.F. induced in it.

EXPERIMENT 116. — Wind several turns of wire on a rectangular frame, mounted so it can be rotated between the poles of a strong magnet (Figure 462). Attach the ends of the wire to separate insulated brass rings set on the shaft that holds the frame. Brass strips should be placed so as to rest on these two rings. Connect these two *brushes* to a sensitive galvanometer and rotate the coil. If the rotation starts

when the coil is at right angles to the lines of force, the galvanometer will show a deflection that increases as the coil approaches the center of the magnet pole, and then decreases to zero as the coil reaches the neutral position after a half turn. As the coil moves through the next half turn, the galvanometer needle is deflected in the opposite direc-

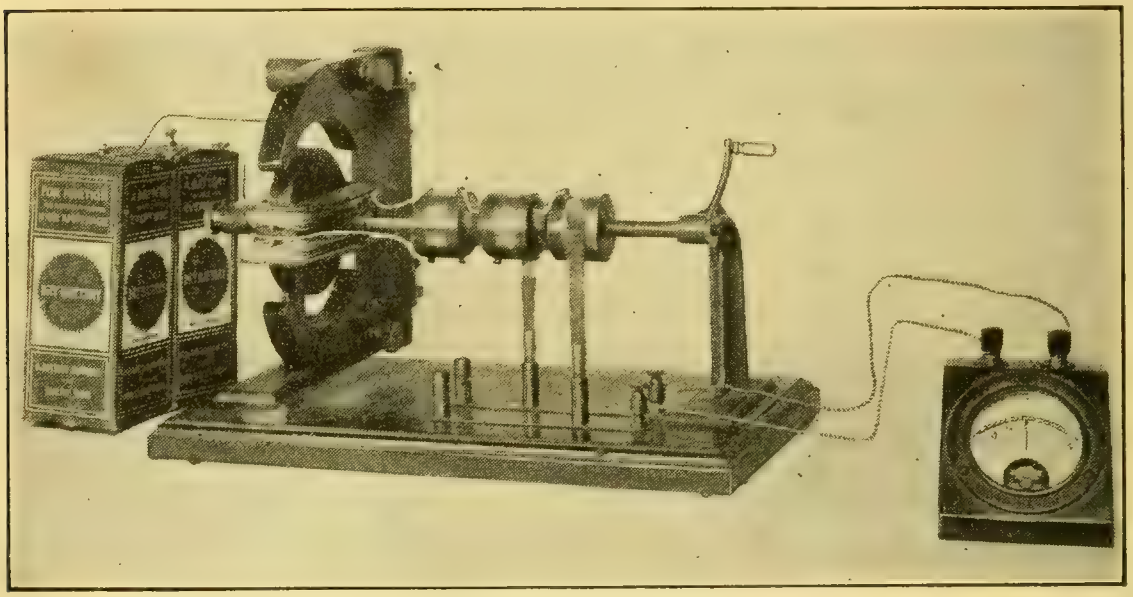


FIGURE 462. — DEMONSTRATION ALTERNATOR.

One end of the coil is connected to the ring at the right; the other end is connected to the center ring. Vertical brass strips act as brushes and connect these rings to the galvanometer.

tion, thus indicating a current in the opposite direction. Every complete rotation of the coil causes an E.M.F. to be induced in the coil first in one direction and then in the other direction.

312. Alternating-Current Generators. — Fleming's rule shows that as the wires on the side of the coil A (Figure 463, left) move *down* through the magnetic field, E.M.F. is induced *toward* the observer. As A moves *up* through the field, an opposite E.M.F. must be induced in it. The other side of the coil B induces an E.M.F. that is opposite that of A but which really pushes current in the same direction through the coil. Since the wires of the coil move across the field, first in one direction and then in the other, the E.M.F. in the coil must be a reversing or alternating pressure. Since in

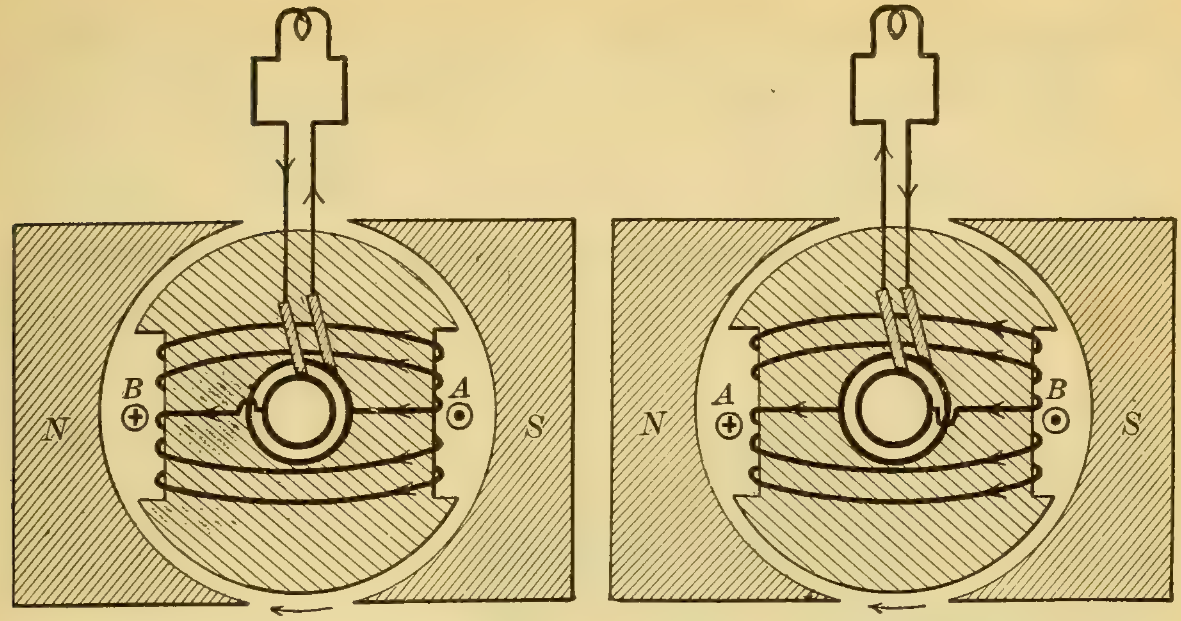


FIGURE 463. — CURRENT DIRECTIONS IN THE ALTERNATOR.

A represents a wire on one side and *B* on the other. The dot indicates a current *out of* the page, and + a current into the page.

this case the ends of the wire are alternately + and −, the rings to which they are attached are alternately + and −, and likewise the brushes that press upon the rings. During one half turn the right-hand brush is + and current flows away from this brush through the galvanometer. During the next half turn, this brush is − and current returns to the generator by this brush. The nature of an alternating current is graphically represented by Figure 464.

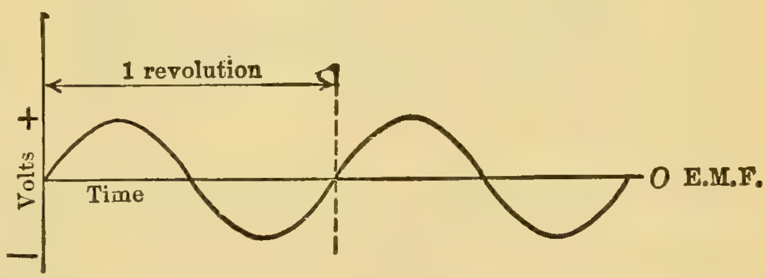


FIGURE 464. — CURVE OF ALTERNATING CURRENT.

Vertical distances show the amount of voltage at different times during the revolution; horizontal distances show the time. The voltage is constantly changing in amount and reverses its direction each half-revolution.

When alternating current (A.C.) is to be produced on a large scale, the procedure is the same, except that more lines of force must be cut per second. In an A.C. generator a

cylindrical iron core is slotted lengthwise at short, regular intervals around its entire circumference. In the slots of this iron core are placed the wires that constitute the armature coil. The ends of this coil are soldered to separate *slip rings*, upon which *brushes* make a sliding contact. A field magnet, usually consisting of several pairs of poles, is energized by a separate direct current, flowing around the poles in such a manner that the poles are alternately N and S. The armature is revolved between the poles of this field magnet by steam or water power. The E.M.F. induced within the armature coil reverses between each pair of poles. If the brushes that make contact with the slip rings are connected, an alternating current will flow through this conductor. In most large commercial machines (Figure 465), the field (P) rotates within a stationary armature (A).

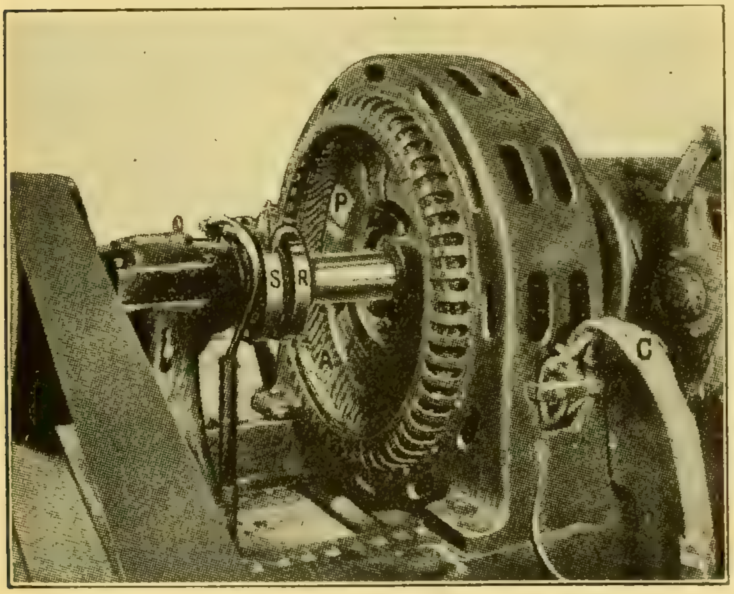
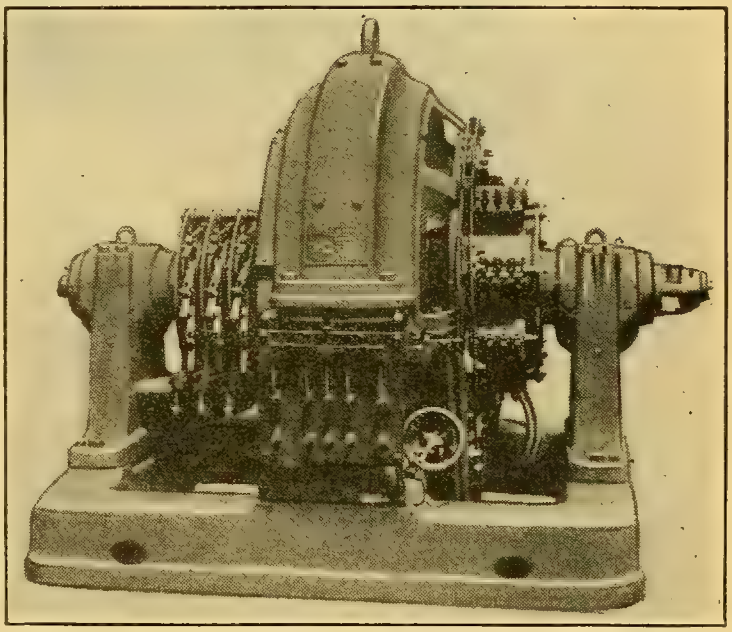


FIGURE 465. — ALTERNATING-CURRENT GENERATOR.

The armature coils (A) are on a stationary frame. The field poles (P) receive direct current through slip rings (SR). The generator delivers current through the cables (C).

Much of the current now produced and used is alternating current. One reason for its widespread use lies in its ease of transformation, a topic that will be considered in another section of this chapter. Alternating current is used for domestic lighting and heating and for the operation of motors for general use. A.C. motors for electric railways were not

at first successful, so most transit lines are now equipped with direct-current systems. Some installations, like the New Haven Railroad and the Chicago, Milwaukee and St. Paul, showed that A.C. could be used successfully for railway work. Alternating current cannot be used for electrochemical purposes, such as charging storage cells, and the various forms of electroplating. When only A.C. is available, it may be rectified (converted into direct current) by devices made for this purpose, as the synchronous converter, motor generator, mercury-arc rectifier, or the vacuum-valve rectifier.

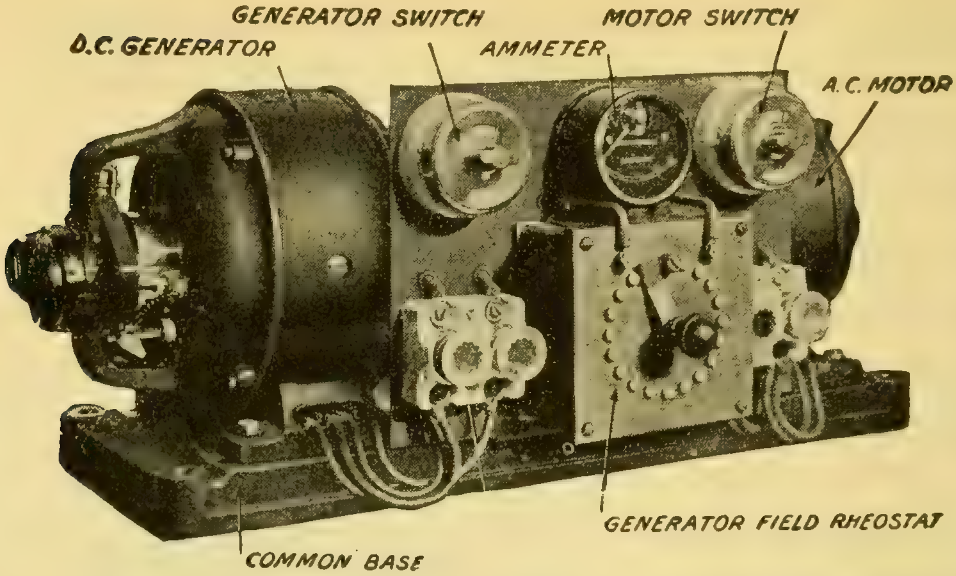


Courtesy Westinghouse Elec. and Mfg. Co.

FIGURE 466. — SYNCHRONOUS CONVERTER.

Alternating current, received through the slip rings at the left end, runs the converter, which delivers direct current from the commutator at the right.

313. Alternating-Current Rectifiers. — The *synchronous converter* (Figure 466) is a combination of an A.C. motor and a D.C. generator in a single machine. Between the poles of a field magnet revolves an armature whose windings are connected to both slip rings and a commutator. Alternating current, admitted through the slip rings, drives the armature as a motor, which causes direct current to be delivered through the commutator. A machine consisting of a separate A.C. motor and D.C. generator, either belted together or mounted on the same shaft, is called a *motor-generator* (Figure 467). The synchronous converter is



Courtesy of Westinghouse Elec. and Mfg. Co.

FIGURE 467. — MOTOR-GENERATOR SET.

The armatures of the motor and the generator are on the same shaft.

rarely used as an inverted converter to change D.C. into A.C.

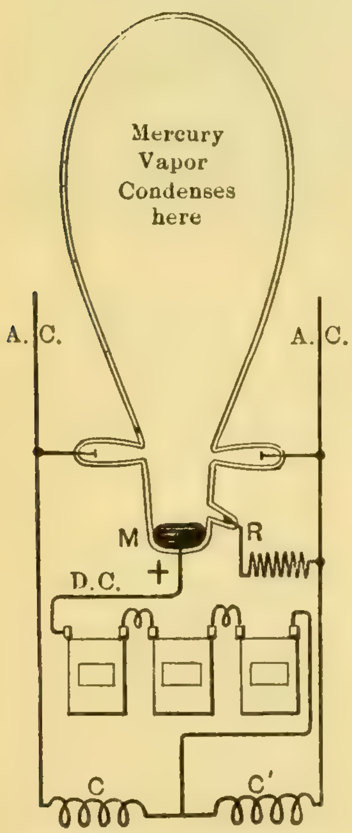


FIGURE 468.—MERCURY ARC RECTIFIER.

A storage battery is shown connected for charging.

A *mercury-arc rectifier* (Figure 468) is often used in garages to obtain direct current for charging batteries. The pool of mercury, M, is the exit for current from whichever of the A.C. side terminals is + at that instant. The current out from M is therefore direct. The electrical inertia of the coils C and C' maintains the flow of current during the moment of current reversal in the A.C. circuit. Depending upon the size of the tube, currents up to 30 or more amperes may be taken from the D.C. terminals.

If lead and aluminum plates are immersed in suitable electrolytes in four cells and connected to an A.C. source as in Figure 469, current will *enter* each cell

only by the aluminum plate. Hence in this *electrolytic rectifier,* if current enters at *A,* it will leave by *C.* On the other alternation, current entering at *B,* also leaves at *C.* Since both alternations leave the cells at *C,* a *direct current* flows from *C* to *D.*

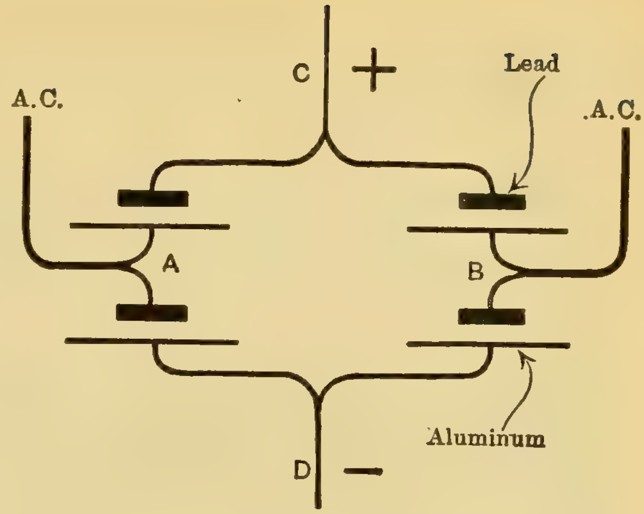
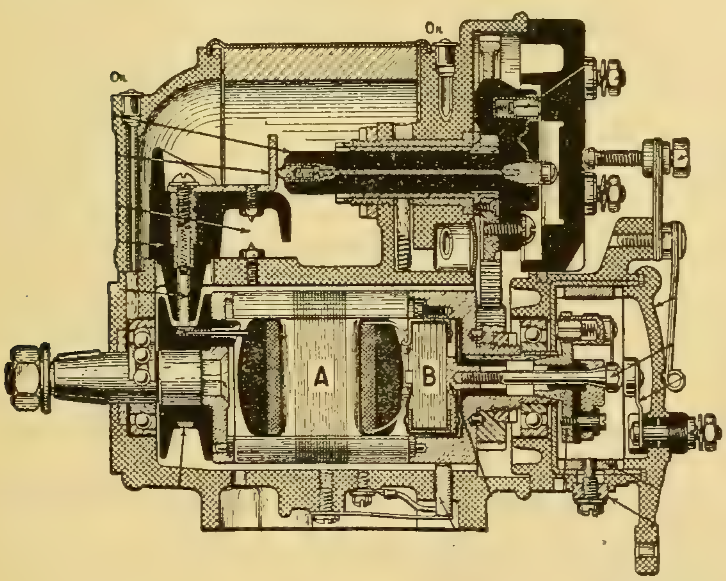


FIGURE 469. — ELECTROLYTIC RECTIFIER, CONNECTION DIAGRAM.

The plates shown at *A* and *B* are immersed in a solution of ammonium phosphate, borax, or sodium bicarbonate.

314. Magnetos. — The magneto is a small A.C. generator consisting of a coil of many turns set in a permanent magnetic field. Either the coil (Figure 470) or the magnet (Figure 471) rotates. The current thus induced within the coil is utilized in ringing telephone bells and also in some automobile ignition systems.



Courtesy Bosch Magneto Co.

FIGURE 470. — AUTOMOBILE MAGNETO, SECTIONED.

The coil *A* rotates between the poles of a permanent magnet.

QUESTIONS

1. What were the early means of producing electrical energy? Why were these means unsatisfactory?

2. How is electrical energy chiefly produced to-day? What process is involved in this production?

3. Give the names of men associated with the modern method of producing electrical energy. For what is each noted?

4. What three things about induction can be found out by the use of a coil of wire, a galvanometer, and a magnet?

5. What factors determine the magnitude of an induced E.M.F.?

6. State the rule for finding the direction of an induced E.M.F. What determines the direction of an induced E.M.F.?

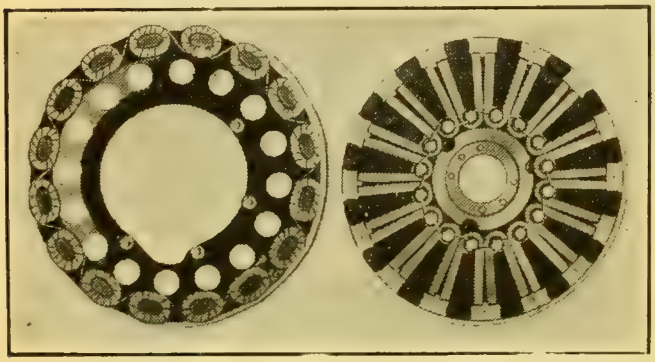
7. What is the meaning of the term *alternating current?*

8. If alternating current is to be caused to flow from the generator, how must the ends of the armature coil be connected?

9. For what purposes is alternating current used? For what purposes is alternating current useless?

10. Is it possible to convert alternating current into direct current? When would such conversion be desirable?

11. How does a magneto differ from an alternating-current generator? State a use of magnetos.



Courtesy Ford Motor Car Co.

FIGURE 471. — FORD MAGNETO.

The coils on the left are connected in series and are stationary. The ring of horseshoe magnets at the right is mounted on the engine shaft and rotates in front of the coils.

315. Direct-Current Generators. — We have seen that the current within the revolving generator coil must be alternating because the coil moves in opposite directions across the magnetic field during each revolution. To cause a direct current to flow through the external circuit of a generator, it is necessary to change the connections to the external circuit so that both alternations of the E.M.F. deliver current in one direction.

316. Commutators. — The following experiment shows the action of the commutator in the generator.

EXPERIMENT 117. — Use a coil, magnets, and mounting similar to that of the previous experiment, but having one end of the coil attached to one half of a single, split, brass ring and the other end to the other

half of the ring (Figure 472). Set the brushes opposite each other, so that each brush will press against the middle of one segment of the split ring at the instant when the coil is opposite the middle of the

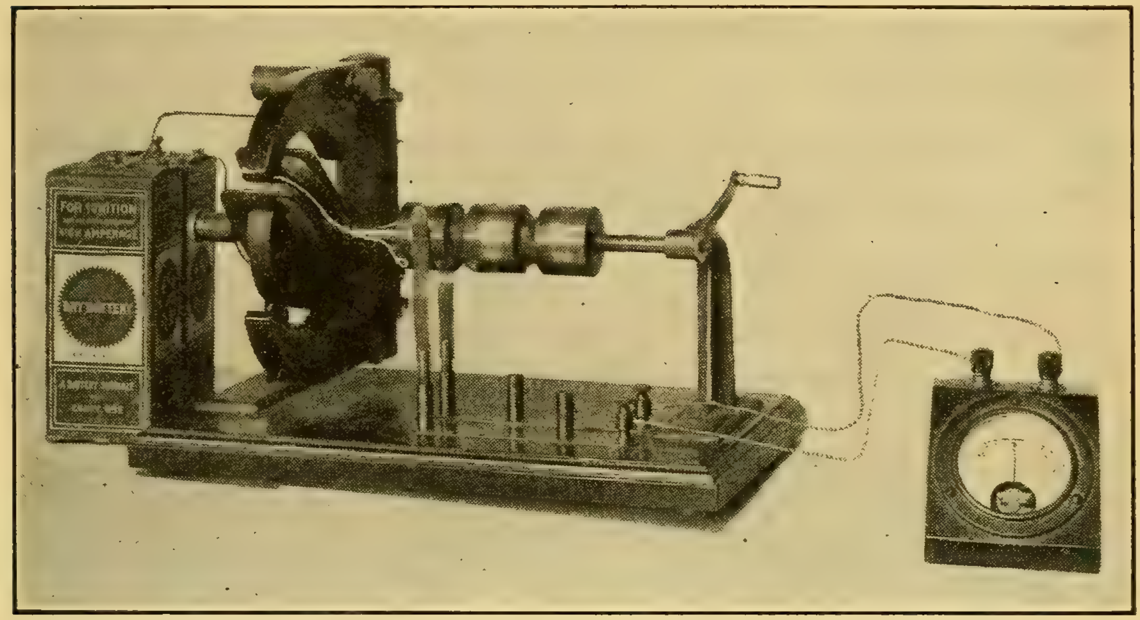


FIGURE 472. — DEMONSTRATION D.C. GENERATOR.

The same coil and magnet as in the alternator are used, but the brushes rest on the two halves of a split-ring commutator.

magnet pole. Connect the brushes to the galvanometer as before and rotate the coil. The galvanometer needle will now indicate a pulsating current that varies in amount but does not reverse (Figure 473).

The split ring of the last experiment is a *commutator* and it serves to change an internal alternating current into an external direct current. The direction of the E.M.F. induced in each side of the rotating coil changes with each half turn, and consequently the polarity of the segments of the commutator changes each half turn. By setting the brushes in the proper position one

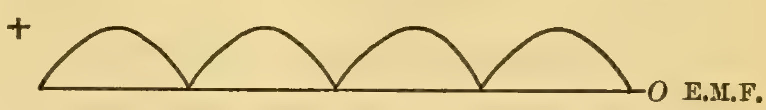


FIGURE 473. — CURVE OF DIRECT CURRENT.

This represents the voltage of a single coil generator during two revolutions. Vertical distances show voltage, and horizontal distances, time. The voltage falls to 0 each half revolution, but is always in the same direction.

brush will be in contact with a segment only at the time when the segment is positive; the other brush touches each segment during the time that it is negative. Current in the external circuit will flow continuously in one direction from the positive to the negative brush (Figure 474).

The construction of the D.C. generator does not necessarily differ from that of the alternator except in the change from

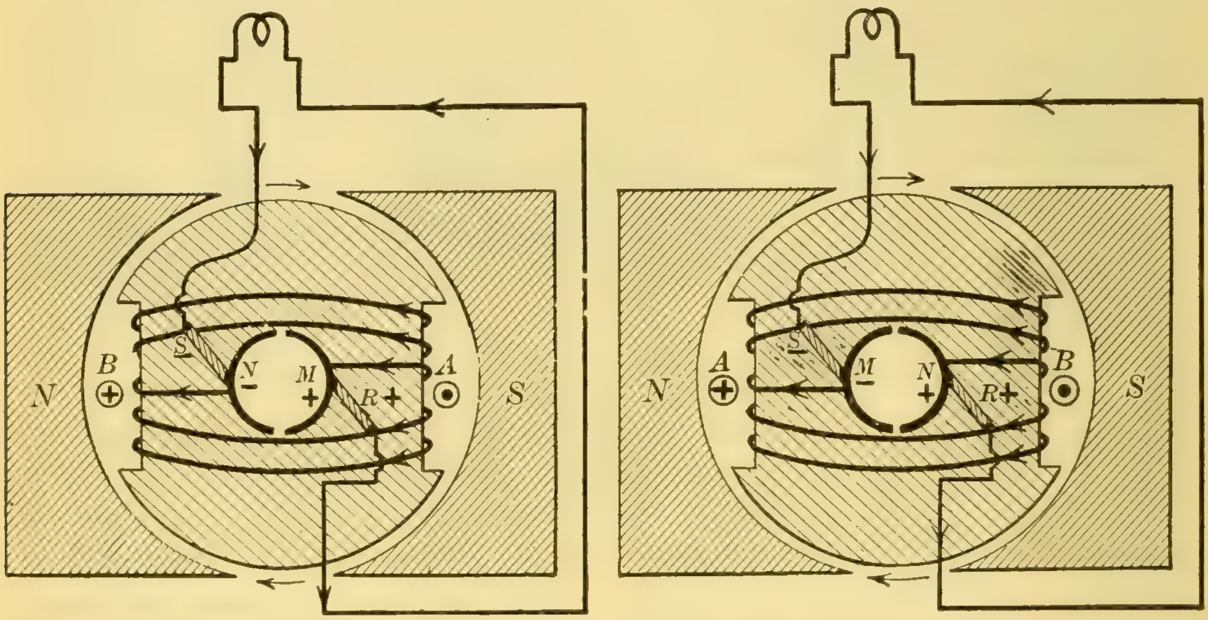


FIGURE 474.—CURRENT DIRECTION IN THE D.C. GENERATOR.

M and *N* are the commutator segments. These change polarity, as shown, but the current always leaves through brush *R* and returns through brush *S*.

slip rings to commutator. We find the multipolar field and the armature core wound about its entire circumference with coils, just as in the D.C. motor shown in Figure 368, page 397. Each of the many coils requires a separate segment on the commutator and there are usually as many brushes as there are poles in the field magnet. The D.C. dynamo commonly uses some of its own current to energize its field magnet. The multiple coils cause a constant E.M.F. to be induced (Figure 475). The strength of this electrical pressure depends upon the turns of the armature, the field

strength, and the speed of revolution of the armature. This voltage may be varied either by changing the speed of the armature or by changing the current that energizes the field by means of a resistance coil (field rheostat), inserted in the field circuit for this purpose.

317. Dynamo Fields. — The dynamo, by which is meant either a motor or a generator, may supply current to its field by one of three methods. As noted, the D.C. genera-

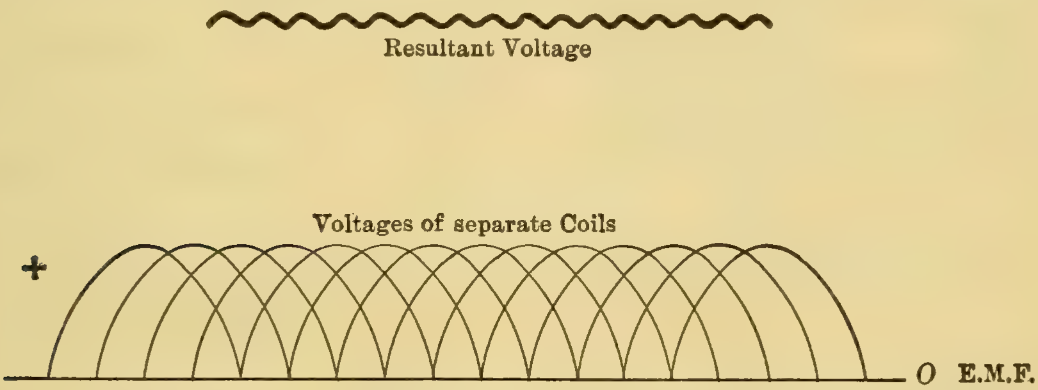


FIGURE 475. — VOLTAGE CURVE OF A GENERATOR WITH SEVERAL COILS. The voltages of the several coils, connected in series, combine to give the resultant voltage to the external circuit.

tors usually energize their fields with current drawn from the machine itself. Enough residual magnetism must remain in the poles so that a little current is produced as the armature is revolved. This current passing through the field coils makes a stronger field and therefore a stronger current. Thus the field is built up to full strength and the dynamo to full voltage in a few seconds. The current from a dynamo is dependent on the voltage of the dynamo divided by the resistance of the circuit (Ohm's Law). A dynamo may, therefore, produce current of any size, but a fuse or circuit breaker limits the current produced to the amount the dynamo wires may carry without being too greatly overheated. The driving power also limits the current.

In a *series-wound* generator (Figure 476) the entire current output of the machine is first passed through the field coils, thence through the external circuit and back to the other generator terminal. The voltage of a series-wound machine increases with the current output, because the field strength increases. This generator is rarely used commercially.

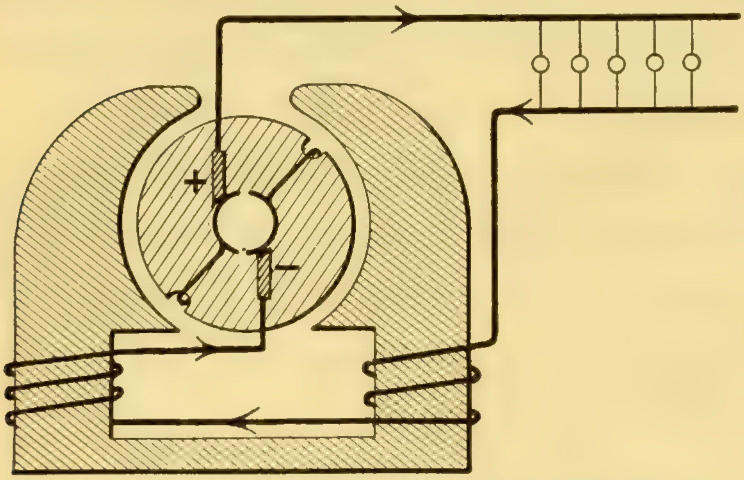


FIGURE 476. — SERIES-WOUND GENERATOR.

All the current passes through the field, and the voltage increases when the current increases.

The *shunt-wound* generator (Figure 477) delivers the greater portion of its output through an external circuit, but a small fraction of the total current is passed through a field coil of many turns. The voltage of this machine falls off as the external current increases. This may be offset to some extent by reducing the resistance of the field circuit.

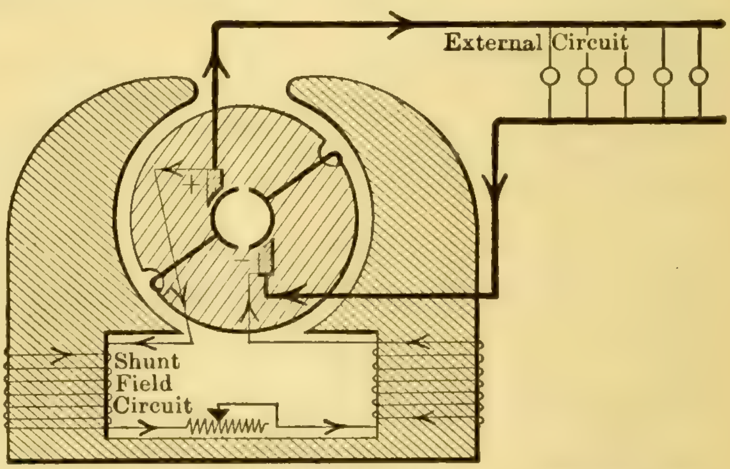


FIGURE 477. — SHUNT-WOUND GENERATOR.

Only a little current passes through a large number of turns in the field coils. Increased current delivered causes some drop in voltage.

The *compound-wound* generator combines the two preceding methods (Figure 478). The current through its series coil tends to offset

the drop in voltage due to its shunt field. This makes its voltage practically constant under all conditions. It is the most common commercial type of generator.

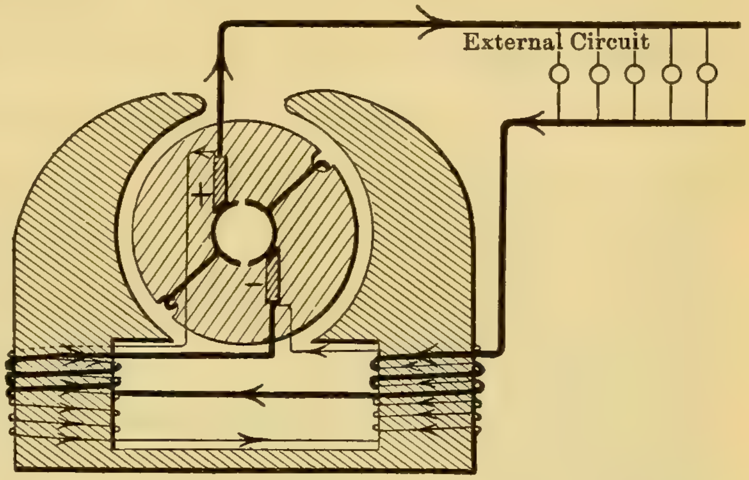


FIGURE 478. — COMPOUND-WOUND GENERATOR. A few series turns on the field coils cause practically constant voltage at all loads.

The ampere-turns must be the same in all three types to produce the same field strength. In all types, however, the amount of energy used in the field coil is only a small percentage of the total output of the generator. Motors, which are users instead of producers of electrical energy, have the same method of field excitation; that is, a wiring diagram of the generator and of the motor would be identical except for the direction of the current arrows (Figure 479). A.C. generators must obtain current for field excitation from a separate D.C. source, usually from a small D.C. dynamo called an *exciter*.

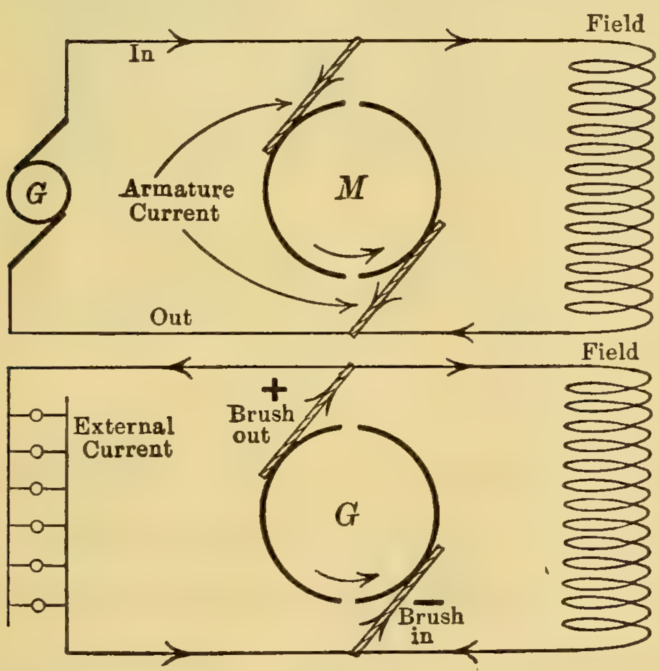


FIGURE 479. — MOTOR AND GENERATOR. The construction and wiring is the same, but the current direction is opposite for the same direction of rotation.

318. Lenz's Law. — The casual observer knows in a general way

that electrical energy is produced at the expense of some other form of energy. It is a matter of common knowledge that dynamos are run by steam engines, water power, or by gasoline engines. It is not so well known that to produce an increased amount of electrical energy more energy from some one of these sources must be demanded.

The relation between mechanical energy consumption and electrical energy production can be shown by a telephone magneto.

EXPERIMENT 118. — Attach a wire to one terminal of the magneto and revolve the coil by means of a hand crank. While still turning the crank, touch the loose end of the wire to the other terminal of the magneto and try to revolve the coil as rapidly as before. While the coil can be turned easily when the coil is delivering no current, it can be turned only at a slow rate when electrical energy is being produced.

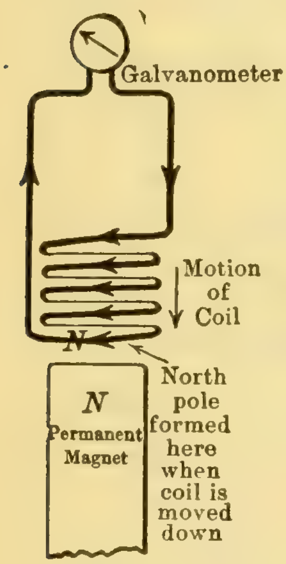


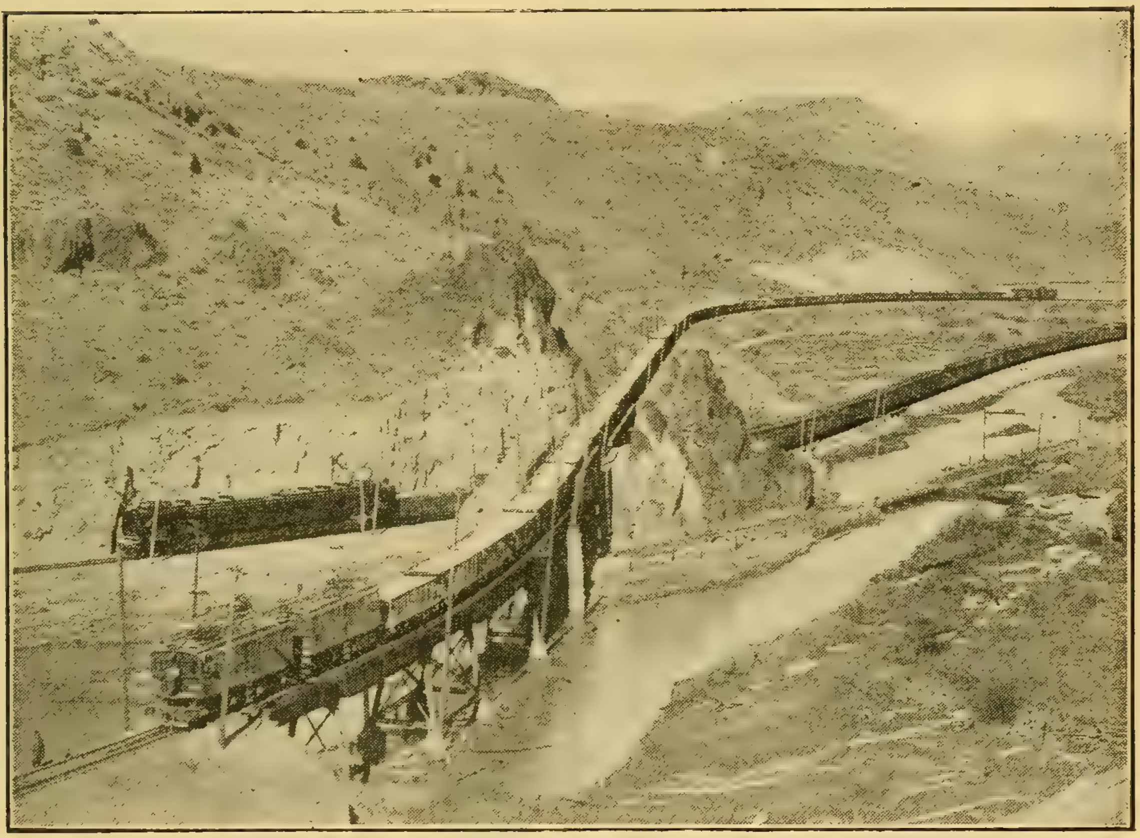
FIGURE 480.

Another simple experiment will show the reason for the additional expenditure of mechanical energy.

EXPERIMENT 119. — Wind a coil of a few turns of wire on a hollow rectangular frame that will slip over the pole of a bar magnet. Connect the coil with a galvanometer (Figure 480). Move the coil over the N pole of the magnet and *note the galvanometer deflection.* Move the coil off the pole and observe that there is an opposite deflection.

If the current is traced back through the coil in the last experiment, it will be found that as the coil approaches the N pole, the coil itself possesses a N pole at the end nearer the magnet. This means that there is a magnetic opposition to the motion of the coil. When the coil is withdrawn, a S pole in the coil will be found nearer to the N pole of the magnet. Again there is a magnetic hindrance to the motion

of the coil, this time an attraction between unlike poles. Other trials will show that every motion of the coil is opposed by either a repulsion or an attraction, even though these forces may not be noticeable to the experimenter. Coming back to the magneto experiment, we find that this hindrance



Courtesy Chicago, Milwaukee and St. Paul R. R.

FIGURE 481. — ELECTRIC TRAINS IN THE ROCKY MOUNTAINS.

In descending the mountains, the motors act like generators and return current to the line.

to the motion of the coil *is* noticeable and we may explain it according to the behavior of the coil. When current flows in the magneto coil, this current magnetizes the core on which it is wound. The poles of this core are always such as to be attracted by the adjacent field pole and it is to break this attraction that additional force is needed.

In a commercial type of generator, the same condition is found. The current induced in the armature coils magnetizes

the core in such a way as to cause a constant attraction between core and adjacent field pole. This attraction, or magnetic drag, must be overcome by the engine that runs the generator. The more current drawn from the generator, the stronger the attraction between armature and field, and the greater must be the expenditure of mechanical energy to overcome this attraction. This means that as you turn on lamps at home, a fireman in a distant power house begins to shovel coal faster. You pay for the additional coal and labor when you pay your electric light bill. Some electric railways (Figure 481) utilize this magnetic drag of generators as follows: motors using electrical energy haul trains up the grades but gravity pulls them down the grades; then the moving train turns the motor armature which generates current and also acts as a brake for the train. Lenz's Law sums up the relations developed in the preceding discussion: *An induced current produces a magnetic field that opposes the motion that causes the induced current to flow.*

QUESTIONS

1. What kind of current flows in the armature coil of a direct-current dynamo? Where does the current become continuous in direction?

2. What is a commutator? On what kind of generator would you expect to find a commutator?

3. What is the purpose of a commutator on a direct-current generator? Compare the purpose of the commutator on a generator with its use on a motor.

4. From what source does a direct-current generator usually obtain the current that energizes its field magnet? Is this true of an A.C. generator?

5. How are D.C. generators classified as to the means of securing proper magnetization of their field magnets?

6. For what purposes is it possible to use direct current? For what purposes is it essential to use direct current?

7. In what respects would a generator used to produce a large amount of electrical energy differ from the simple machine described in Experiment 117?

8. State Lenz's Law. What is implied in this law concerning the relative difficulty of making large currents and small ones?

9. What increased expenditure by the electric power company results when a consumer turns on additional lamps in his home?

10. How do some electrified railway systems utilize the difficulty in turning a generator which is producing electrical energy?

319. Currents from Currents. — In a generator, lines of force are cut by revolving wires, or in some cases, stationary wires cut the lines of force of a revolving field. It is possible, however, to induce an E.M.F. even if no material part of the device moves.

Experiment 120. — Wind a few turns of wire on an iron core and connect this coil through a push button to a cell. On a hollow cylinder large enough to slip over the first coil, wind many turns of fine wire and connect the ends to a galvanometer (Figure 482). Put the second coil in position over the first and press the button. A momentary current is indicated by the galvanometer, but this current dies away quickly even though the current in the first coil continues to flow. Release the button and a momentary current flows through the secondary coil in the opposite direction.

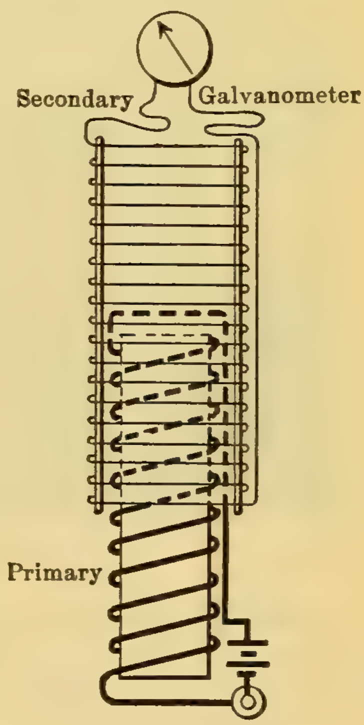


Figure 482.

Repeated trials show that current in the secondary coil flows only when current in the primary coil is undergoing a change. The primary coil is an electromagnet whose lines of force expand as the current is turned on and collapse as the current is turned off. The turns of the secondary cut these lines of force as the lines spread out from the primary and again as they collapse into it when the primary circuit

is broken. Thus E.M.F. may be induced in one coil (secondary), if this coil is near enough to another coil (primary) to cut the lines of the varying field of the primary. If the circuit of the secondary coil is closed, the E.M.F. causes a current to flow.

320. The Induction Coil. — A Ruhmkorff induction coil (Figure 483) is essentially the same device as that described

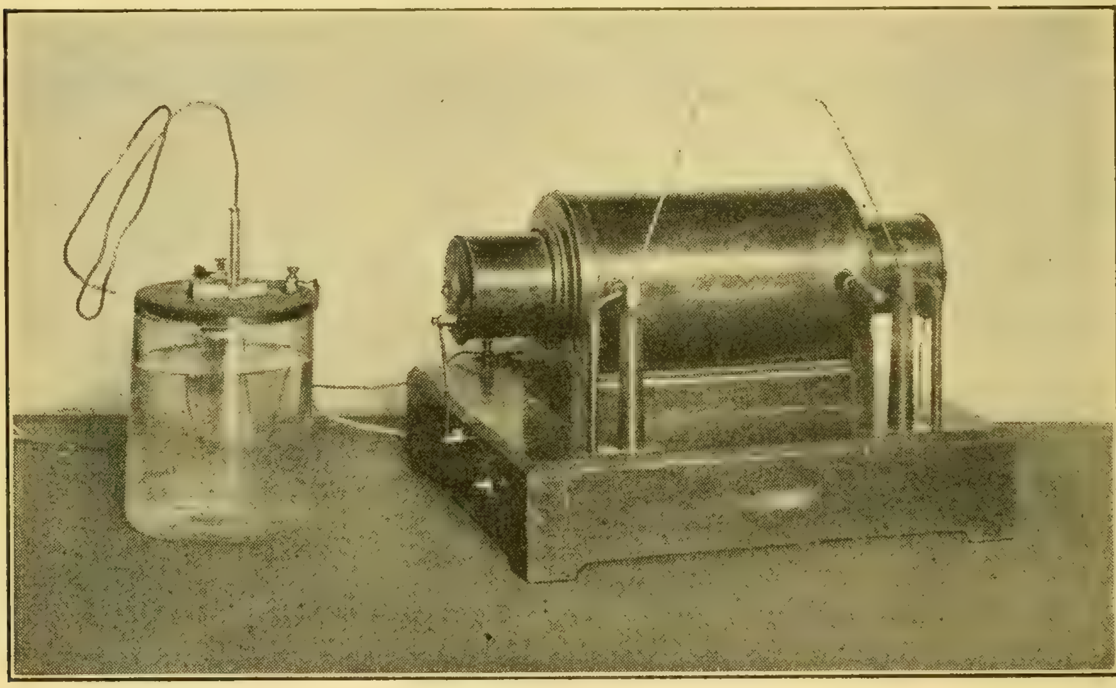


FIGURE 483. — INDUCTION COIL.

The primary is wound on the long inner cylinder and the secondary on the outer cylinder. The jar at the left is an electrolytic interrupter, that makes and breaks the circuit many times each second.

in the preceding experiment, including a mechanism to make and break the primary circuit. The primary coil consists of a few turns of heavy wire wound on a core of iron rods. The primary is connected through an automatic vibrator (Figure 484) like an electric buzzer (§ 232) to a low-voltage source of current. The secondary, consisting of thousands of turns of fine wire, is placed outside the primary. Each time that the current in the primary is interrupted by the vibrator, the

strong primary field collapses quickly past the many turns of the secondary. The rapid cutting of the lines of force of this field by the secondary induces a very great E.M.F. in the secondary. This E.M.F. is large enough to overcome the resistance of air gaps and cause a spark to pass between separated terminals. Use is made of this high voltage in the spark plugs of automobiles, for wireless transmission, and for X-ray tubes.

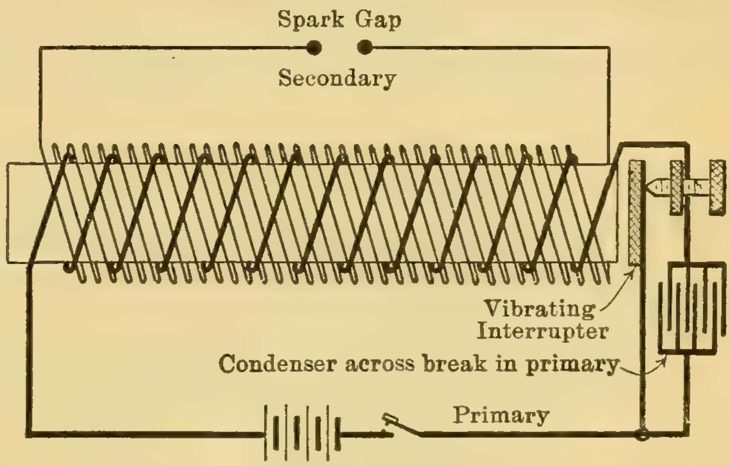


FIGURE 484. — INDUCTION COIL, CONNECTION DIAGRAM.

321. Self-induction. — Whenever a direct current in a circuit containing an electromagnet is broken, a spark is seen to pass across the opening gap. This spark depends upon the size of the current and upon the dimensions of the electromagnet, but it is always much greater than the applied E.M.F. of the circuit could cause. When the current ceases, the field about the magnet decreases and this shrinking field is cut by the turns of the magnet itself. The cutting of its own field by the magnet coils *self-induces* a large E.M.F. in the magnet coils. This E.M.F. tends to prolong the flow of the electricity of the coil, and is great enough to cause the flaming spark that often occurs as D.C. switches are opened. When such a circuit is closed, the field expanding about the magnet is also cut by the coils, causing an E.M.F. which retards the growth of current in the coil. Thus we see that self-induction (*inductance*) acts as electric inertia that opposes any change in the flow of the current.

Self-induction is of little consequence in D.C. circuits, but in A.C. circuits it is of great importance, especially in transformer primaries (§ 325). In some cases undesirable self-induction can be prevented by winding coils in both directions.

322. Induction Coils in Telephone Circuits. — While unknown in the earlier telephone circuits, the induction coil is now an important adjunct to the commercial telephone. To understand its use we must first become acquainted with the other devices in the telephone circuit, the transmitter and the receiver. The *transmitter* (Figure 485) consists of a flexible disk attached to a carbon button. Behind this button is a carbon box filled with carbon grains that make contact with the button. A low-voltage direct current flows through the primary of an induction coil to the back of the box, through the granules to the button and thence back to the battery. Sound waves striking on the disk cause it to vibrate as frequently as the vocal cords of the speaker. Condensations push in the flexible disk and press the granules in the box more closely together; this reduces the resistance in the circuit and increases the current in the primary so that a magnetic field expands about the secondary of the coil. The rarefactions bring about the reverse effects. The secondary of the induction coil cuts the expanding and contracting field of the primary and induces in itself a current that alternates with each vibration of the speaker's voice.

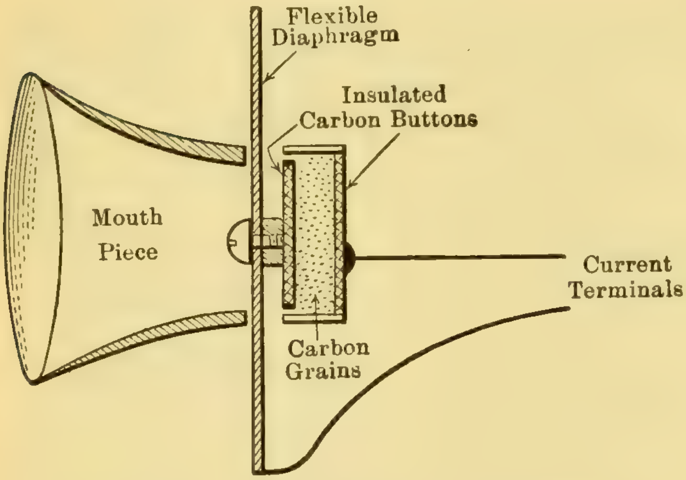


FIGURE 485. — TELEPHONE TRANSMITTER.

An alternating current, therefore, flows through the line connecting the subscribers.

323. The Receiver is a U-shaped permanent electromagnet set near a flexible *iron* disk (Figure 486). Since an alternating current flows through this magnet coil, it is obvious that one alternation of the current will strengthen the magnet and draw in the iron disk; the following alternation must necessarily weaken the poles and let the disk spring out again.

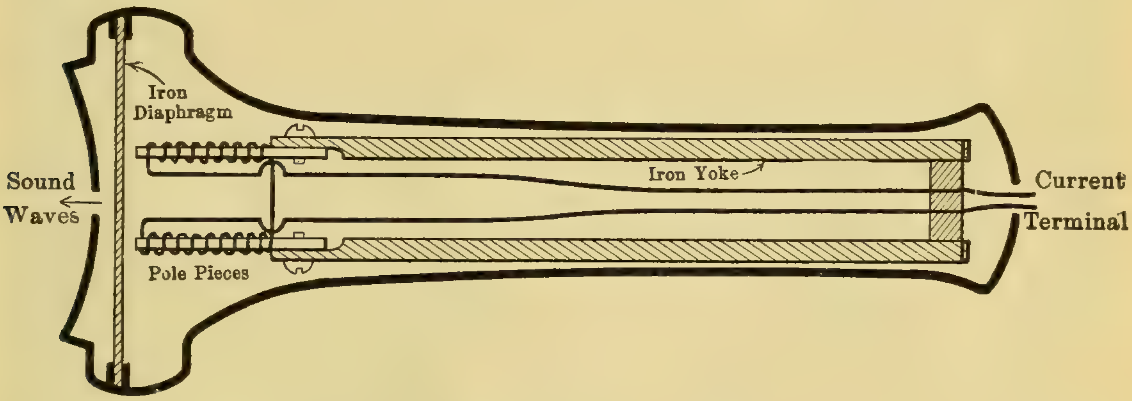


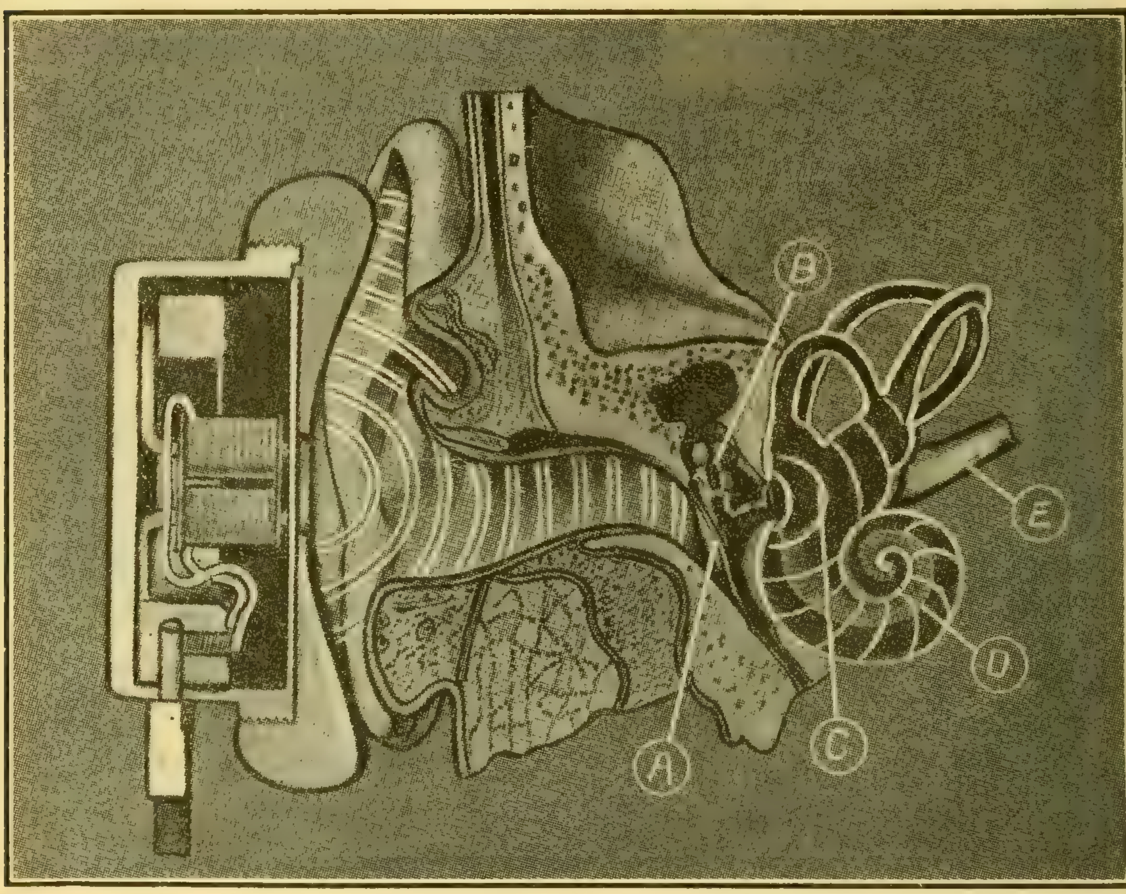
FIGURE 486. — TELEPHONE RECEIVER.

The soft iron pole-pieces are attached to the poles of a permanent horseshoe magnet.

The iron disk of the receiver vibrates as fast as the current alternates; this occurs as frequently as the transmitter disk is vibrated by the speaker's voice. The vibration of the receiver disk sets up in the air a series of sound waves exactly like those emitted by the speaker (Figure 487). The transmitter is a device to vary the resistance of a circuit as sound waves fall upon it. The induction coil converts a variable D.C. into an A.C. The receiver converts the alternating pulses of electrical energy into a series of audible sound waves. The combination of instruments is exceedingly sensitive, so that small currents are sufficient for their operation.

EXPERIMENT 121. — Connect a telephone receiver and a 25-watt tungsten lamp in series to a 110-volt A.C. circuit and determine the

effect on the receiver. The receiver will hum with a note whose frequency is the same as that of the current, viz., 120 (60 cycles) vibrations per second. This shows the response made by the receiver to an alter-



Courtesy of Western Electric Co.

FIGURE 487. — HEARING WITH THE TELEPHONE.

The sound waves produced by the diaphragm of a receiver are shown entering the ear and striking the ear-drum (*A*). The movable chain of bones (*B*) transmit the vibrations of the drum to the fluid of the inner ear and set up waves (*C*) in it. These strike nerves (*D*), each tuned to a single vibration, and the nerve filaments unite in the auditory nerve (*E*) leading to the brain.

nating current. In this case the frequency is fixed, instead of depending on the voice of the speaker.

QUESTIONS

1. Is it possible to induce an E.M.F. without moving some part of the induction device?

2. Describe a simple experiment to show that currents of electricity may induce an E.M.F. in adjacent wires. What is such a device called?

3. In a simple induction coil, when will an E.M.F. be induced in the secondary coil?

4. Why is the frequent interruption of the primary current necessary in an induction coil?

5. How does the primary voltage of an induction coil differ from the secondary voltage? What is the general purpose of induction coils?

6. State a use of induction coils, telling exactly why the coil is used for this purpose.

7. What is meant by self-induction? When does self-induction occur in a coil?

8. What effect do sound waves have upon a telephone transmitter? What kind of current flows through a telephone transmitter?

9. What change takes place in the magnetic field surrounding the primary of a telephone induction coil when a person speaks into the transmitter? What is the effect of these changes upon the secondary coil of the induction coil?

10. What kind of current flows through the secondary of a telephone induction coil? What kind of current flows in the line connecting the speaker and the hearer?

11. What kind of current flows in the receiver magnet of a telephone? How does this current affect the strength of the magnet?

12. How do the variations of strength of the receiver magnet affect the iron diaphragm of the receiver? What disturbance is set up by this operation of the receiver diaphragm?

324. Transformers. — It has been noted that A.C. is widely used because of the readiness with which its voltage can be raised or lowered. We are now ready to consider why this is desirable and how it is possible. An experiment will show the answer to the second question.

Experiment 122. — Wind several hundred turns of insulated wire on one half of an iron ring and twice as many turns on the other half (Figure 488). Connect the small coil to a source of alternating current and the larger coil to an A.C. voltmeter with a 220-volt range. Pass current through the primary coil attached to the A.C. source and note the deflection reading of the voltmeter attached to the secondary. Also attach the voltmeter to the primary terminals. The secondary voltage

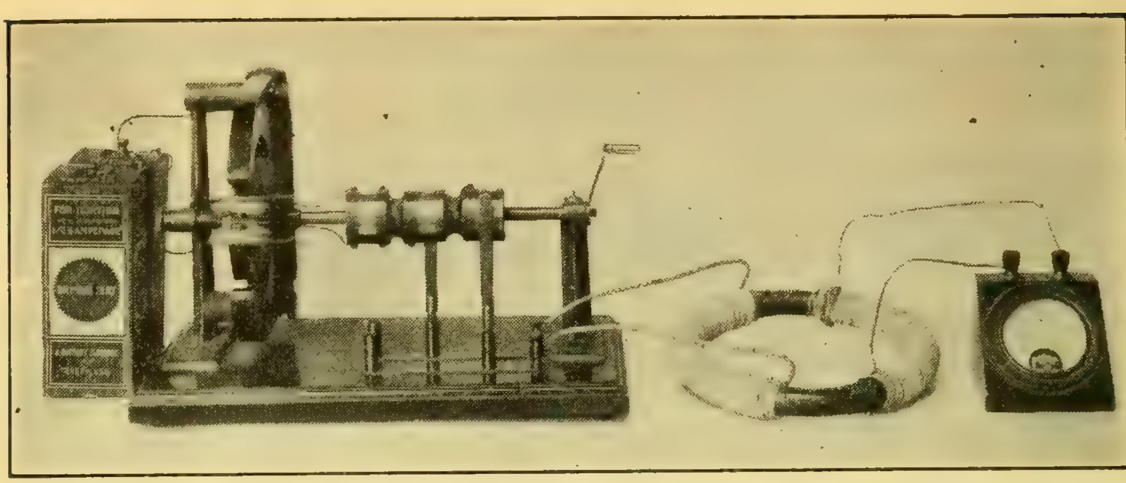


FIGURE 488. — ALTERNATOR AND TRANSFORMER.

The iron ring with primary coil connected to generator and secondary to galvanometer is a copy of that used by Faraday in his discovery of induction. For use with 110 volts, many more turns should be wound on the ring.

will be found to be double the primary voltage. This device, consisting of two entirely separate coils wound on an iron core, has *stepped up* the voltage to twice the former pressure. Now reverse the connections, making the larger coil the primary, *i.e.* attached to the source of current, and the smaller coil the secondary. The voltmeter reading will show that the voltage of the primary has been *stepped down* to one half its former value in the secondary.[1]

A.C. voltages may be transformed to any higher or lower value by connecting the available supply to a transformer with the proper ratio of turns in the primary and secondary coils. The secondary voltage will bear the same ratio to the primary voltage that the number of turns in the secondary bears to the primary

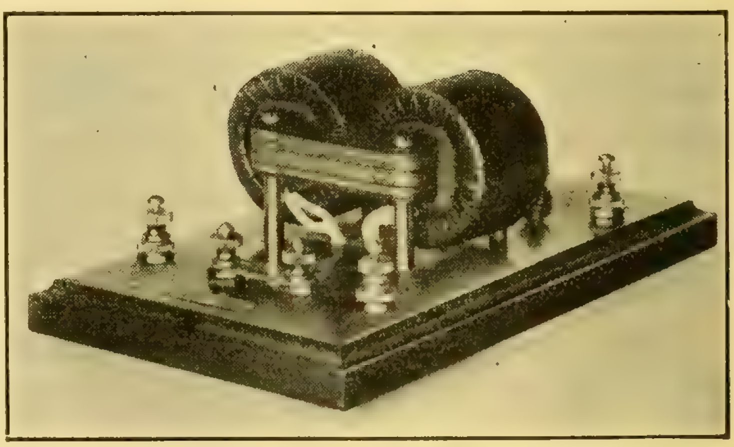


FIGURE 489. — THIS DEMONSTRATION TRANSFORMER MAY BE USED ON 110 VOLTS.

[1] Demonstration transformers (Figure 489) may be obtained from apparatus dealers to show the facts of this experiment.

turns. The *volts per turn* are the same in each coil. If a commercial transformer and A.C. ammeters are available, it can be shown that the amperes of current flow in the two coils vary almost exactly in *inverse ratio* to the turns of the coils. Hence, neglecting a slight loss in the secondary, the volts × amperes in the primary = volts × amperes in the secondary. The input of energy is only a little greater than the useful output.

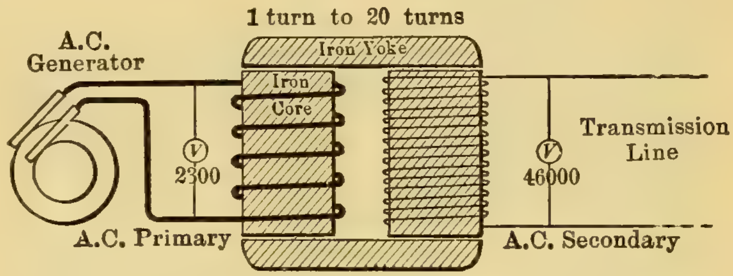


FIGURE 490.—STEP-UP TRANSFORMER, CONNECTION DIAGRAM.

325. Theory of the Transformer. — Alternating-current generators are designed to produce an E.M.F. that reverses either 50 or 120 times per second (25 or 60 cycles). The primary coil attached to such a source of current becomes an electromagnet whose field must reverse as often as the current does. This reversing field, threading through the iron core, is cut by the turns of the secondary coil. An E.M.F., the amount of which depends upon the number of turns in the coil, is induced in the secondary. When the secondary turns exceed the primary turns, the transformer is a *step-up* (Figure 490); when the secondary has fewer turns than the primary, a *step-down* transformer results (Figure 491). The primary coil also *cuts its own lines of force* and by *self-induction* forms *a counter E.M.F.* that automatically regulates the current input on the primary

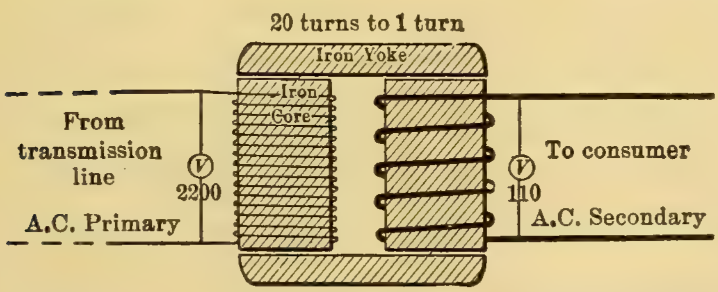
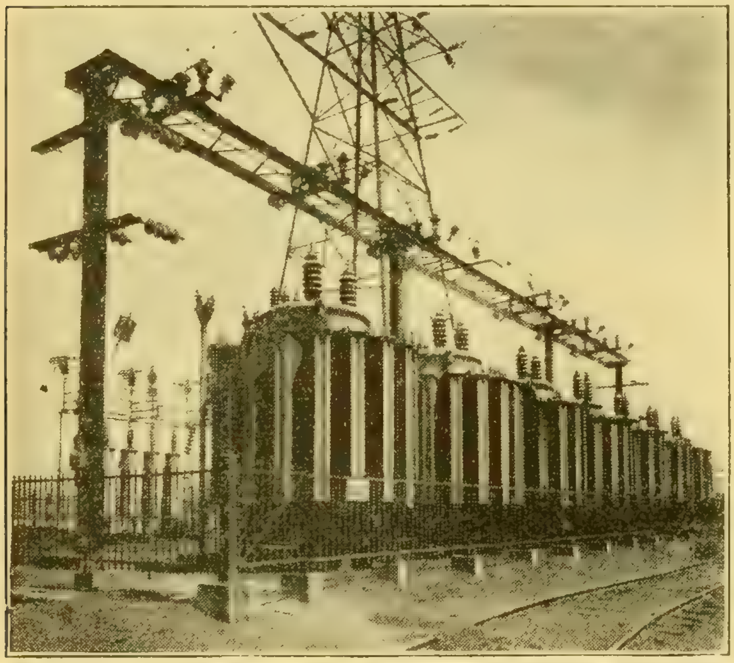


FIGURE 491.—STEP-DOWN TRANSFORMER, CONNECTION DIAGRAM.

side. When no current is drawn from the secondary, the primary current is practically zero because of the self-induced counter E.M.F. (§ 321). When a large current is drawn from the secondary, this self-induced E.M.F. decreases and a correspondingly large current flows in the primary. So efficiently is input regulated to output in the transformer that the loss involved in its operation is only from 1 to 5%.



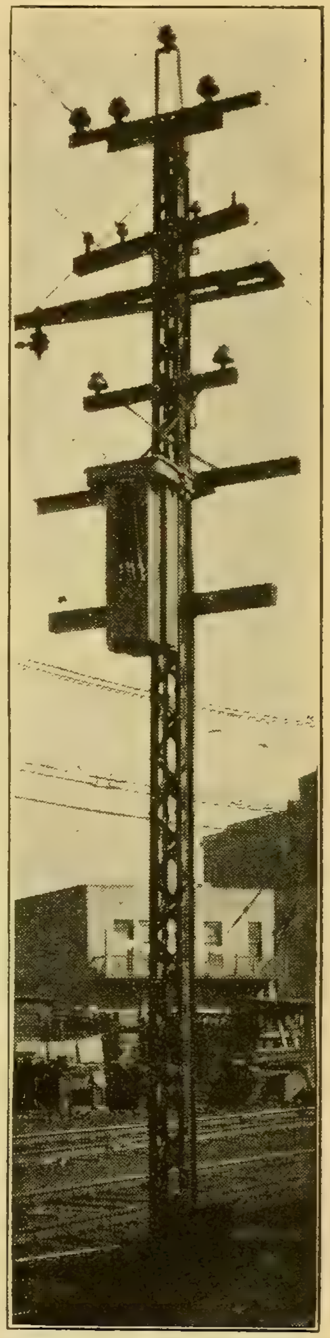
Courtesy Westinghouse Elec. and Mfg. Co.

FIGURE 492. — AN OUTDOOR TRANSFORMER STATION.

These transformers raise the voltage for transmission.

326. Reasons for Voltage Transformation. — Energy of any kind is expensive to transmit and electrical energy is no exception. Energy is lost in the form of heat as current is pushed through a wire against resistance. This heat loss is proportional to the square of the current in amperes and to the resistance of the circuit. The resistance of transmission circuits is made as small as the cost of the large copper wire permits. The current is made small by means of a step-up transformer (Figure 492). This transformer, located at the power house, receives from the generator a certain amount of energy at low voltage and high amperage and delivers approximately the same quantity of energy to the distributing line at high voltage and low amperage. Since the high voltage of the transmission line is unsafe for general use, the

current is passed through a step-down transformer located near the place where the energy is to be utilized (Figure 493). Such a transformer can be found at street intersections, in large buildings, or elsewhere near the final consumer. These step-down transformers receive from the transmission line a high-voltage, low-amperage stream, which they convert into a low-voltage stream whose amperage depends upon the use to which it is put. A diagram showing the essentials of a power circuit is shown in Figure 494.



Courtesy Westinghouse Elec. and Mfg. Co.

FIGURE 493.

327. Electric Power Systems. — Before closing the work on induction, we should get a brief view of the subject in its relation to our daily life. We cannot see the entire process by which current is made and distributed, but we can piece the parts together to make a whole. The most interesting place to see the beginning of this process is at Niagara Falls, where a number of companies have established power houses for the conversion of the energy of the waterfall into electrical energy. These companies have diverted some of the water from the river above the falls and have caused it to fall through vertical pipes, or penstocks, to the level of the river below the falls — a distance of more than 160 feet. At the bottom of the huge penstocks are placed water turbines, whose blades are revolved by the force of the falling water. A shaft from the turbine turns the direct-current field magnet

inside a stationary set of coils. As the poles of the D.C. field move past these coils an E.M.F. is induced in the coils. This

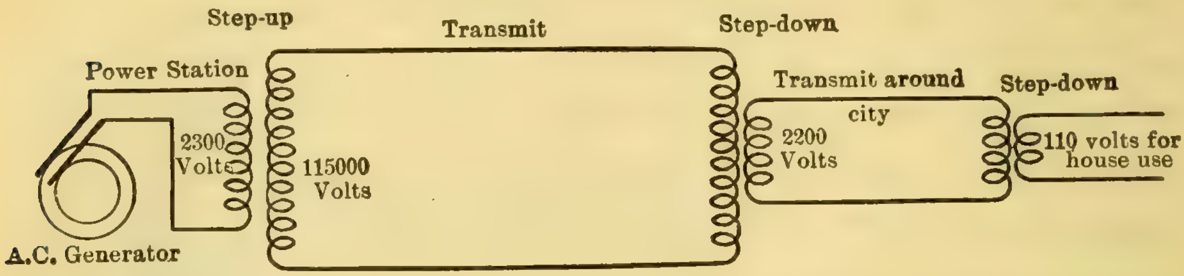


FIGURE 494. — DIAGRAM OF A.C. DISTRIBUTION SYSTEM.

E.M.F. is alternating because the poles that go past the coils are alternately *N* and *S*. Such a power system is described in detail in Chapter XXXIII.

This induced E.M.F. is applied at once to the primary coils of step-up transformers. From the secondary of the transformers a high-voltage current is taken off on carefully insulated transmission lines (Figure 495). This electrical energy is used by cities many miles away from the source of the energy. Before the energy can be used, however, the pressure must first be reduced by a step-down transformer. By this transformer the pressure is reduced perhaps from 50,000 volts to 2200 volts. At this pressure the energy is distributed to various sections of the city. But 2200 volts is still too much for ordinary use, so the trolley company applies the 2200 volts to a step-down transformer and obtains a lower pressure which it may then use in a rotary converter to

Courtesy Niagara Falls Power Co.

FIGURE 495. — TRANSMISSION LINE.

produce 550-volt direct current for the trolley motors. A manufacturing establishment using 220-volt A.C. motors applies the 2200 volts to a 10 : 1 step-down transformer and obtains the required pressure for its motors. The lighting company uses a 20 : 1 step-down transformer on street intersections and delivers energy at 110 volts pressure to supply consumers with electricity for lamps, small domestic motors, and for domestic heating devices.

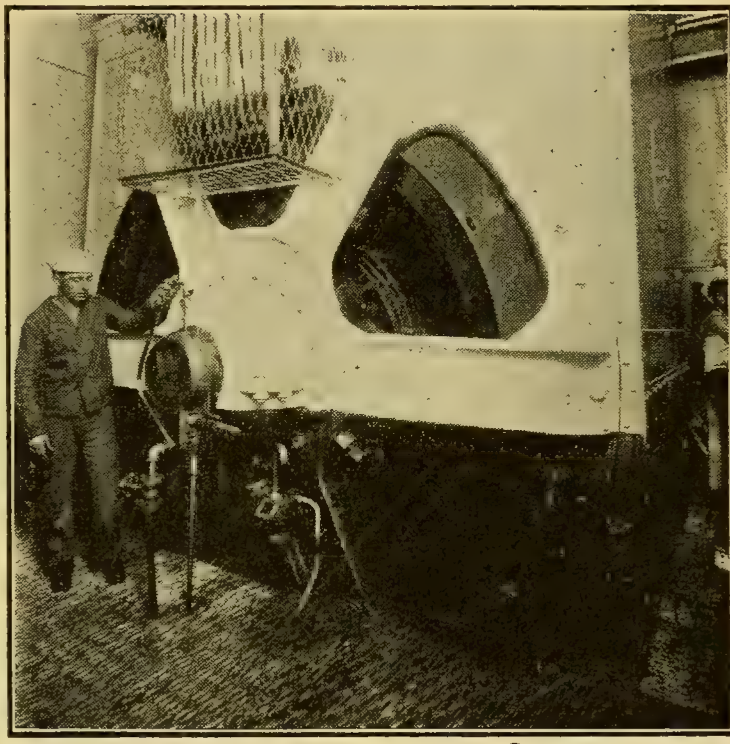


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FIGURE 496. — ONE OF THE MOTORS DRIVING A U. S. BATTLESHIP.

On some battleships, steam from the boilers is caused to turn steam turbines, which in turn rotate the moving part of a generator. Current from this generator is applied to motors (Figure 496) which revolve the propellors of the ship. Although this seems like an indirect method of transmitting energy for so short a distance, it has certain advantages in flexibility and ease of control (Figure 497).

Localities remote from available water power must depend upon steam power for the rotation of generators. This of course makes the electrical energy much more expensive than that obtained from water power. Constant improvement in the transmission of electrical power has made possible its distribution over wide areas that formerly relied upon

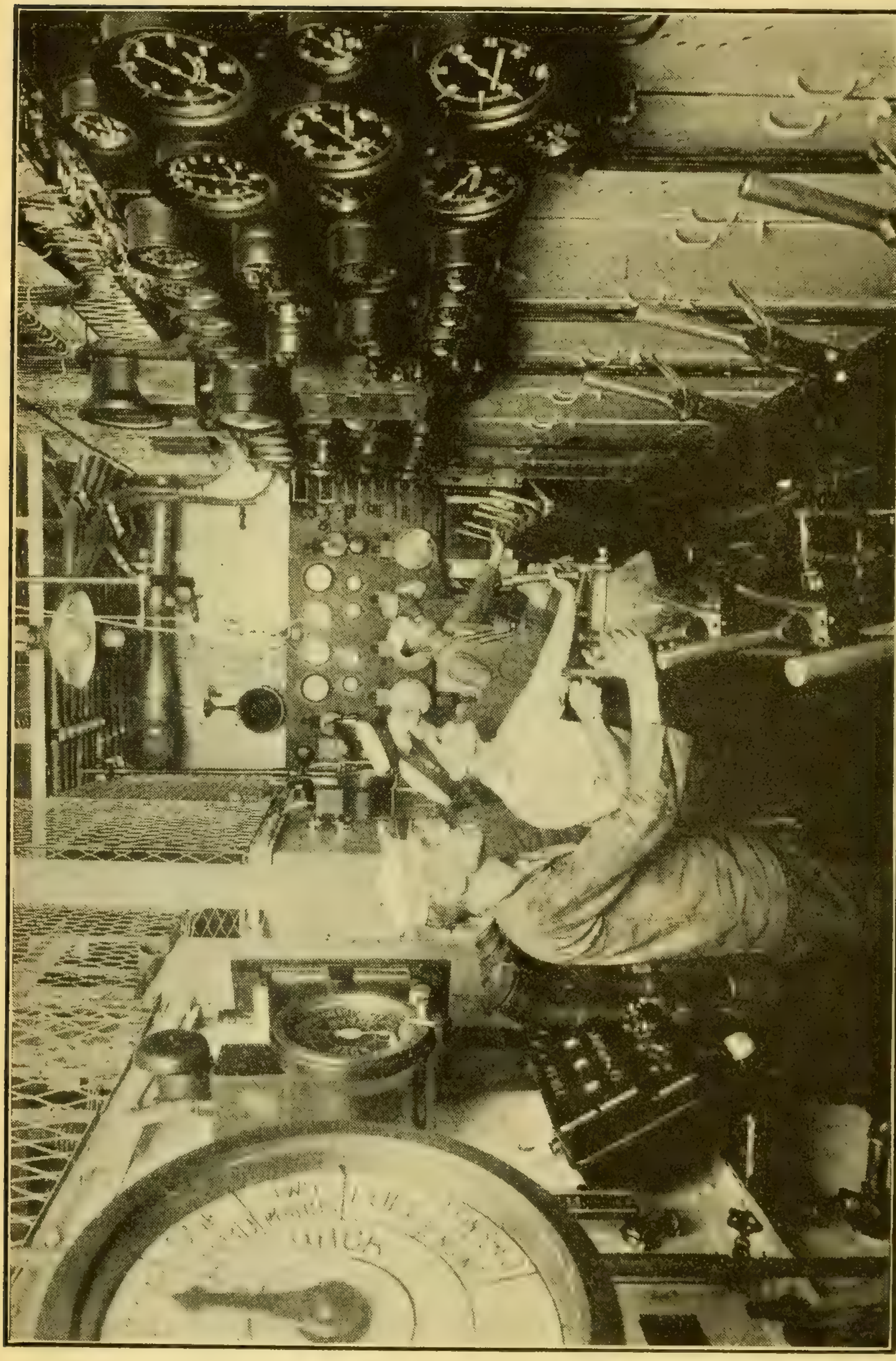

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FIGURE 497. — ELECTRIC BATTLESHIP CONTROL ROOM.

Electric and other meters at the right inform the operating crew of all electric and steam conditions in the ship. The switches controlling the driving motors and the valves in the steam lines are thrown by the switches in the center. The dial at the left shows the orders from the navigating bridge.

steam. An extension of this substitution will not only save coal but will also relieve the railroads of a great burden of carrying coal both for themselves and for consumption by others.

QUESTIONS

1. What kind of current is supplied to transformers? What kind of current is delivered from the secondary coil of a transformer?

2. What is the theory in regard to the production of an E.M.F. in the secondary of a transformer?

3. What is the principal reason for raising voltage by means of a transformer? What is the reason for lowering voltage?

4. Draw a simple transformer, labeling its parts and indicating its effect upon voltage.

5. What must be the ratio of turns on the primary and the secondary of a transformer, if the voltage of 2200 volts is to be reduced to 110?

6. What will be the current in the primary of the transformer in Question 5 when 30 amperes flow in the secondary?

7. A transformer has 500 turns in its primary coil and 4000 turns in its secondary. What will be the voltage in the secondary if the primary voltage is 110?

8. If 5 amperes flow through the secondary circuit of the transformer in Question 7, what will the current in the primary be? If there are 8 amperes in the secondary, how many in the primary?

9. How would you construct a transformer whose secondary voltage will be suitable to light a parallel system of 12-volt Christmas tree lamps, if the primary source has a pressure of 108 volts?

10. Alternating current is to be produced at a waterfall and delivered at a distant city. What should be the parts of a simple system for the economical delivery of energy to the city?

11. By using transformers, how many voltages may be obtained from an A.C. generator? Is such a range of voltages possible in a D.C. system? Why?

12. If you were to equip a new city with an electrical system, would you install an A.C. or a D.C. system? Why?

13. What industries or occupations would be obliged to secure power from an independent source as a result of your choice?

SUMMARY

An **electromotive force is induced** in a conductor by the movement of a conductor across a magnetic field or a movement of lines of force across the conductor. The **direction** of this E.M.F. is determined by the direction of the field and of the motion according to the Fleming rule (§ 310). The **magnitude** of this E.M.F. depends upon the number of lines of force cut across by the conductor per second, this in turn depends upon the number of lines of the magnetic field, the rate of motion of the conductor, and the number of turns of the conductor.

An **alternating-current generator** consists of a series of coils of wire wound on an iron core, and a direct-current field magnet arranged so that either the coils or the magnet may rotate. The ends of the coils are connected to continuous metal slip rings. The rotation of the moving part induces an alternating E.M.F. in the coils. Current may be taken from the generator at the slip rings by means of stationary brushes.

A **direct- or continuous-current generator** differs from the alternating type in that the ends of the inducing coils are connected to the segments of a divided metal ring, called a **commutator.** Brushes, usually of carbon, rest on this commutator and are placed in such position that one touches the commutator segments during the time that the segments are +, while the other brush touches the segments during the time that the segments are −. Thus the brushes have a fixed polarity although they rest upon segments that change from + to − as the coils change position with reference to the field poles.

Direct-current generators commonly furnish current to their own field magnets. A fraction of the normal output may be diverted to the field, making a **shunt-wound dynamo.** The entire current output may be passed around the field poles before being delivered to the external circuit, making a **series-wound dynamo.** Or a combination of these two methods may be used, making a **compound-wound machine**, the usual commercial form.

Lenz's Law states that the magnetic field about an induced current hinders the motion by which the current is induced. This law is an application of the law of reaction, and of the law of conservation of energy.

An E.M.F. may be induced in one coil by **changing the magnetic field** about an adjoining coil.

In the **primary** of an **induction coil**, current is turned on and off by an automatic interrupter, thus causing a variable magnetic field about this coil. A secondary coil, placed outside of this primary, is cut by the expanding and collapsing field of the primary, thus inducing a large E.M.F. in the secondary.

Self-induction results from the cutting of the lines of force about a coil by the turns of the coil itself. Self-induction acts as an electrical inertia which tends to prevent current from entering the coil and to prevent it from stopping after being turned off.

The **transmitter of a telephone circuit** makes use of the varying resistance of carbon under different pressures to vary the strength of a direct current. An **induction coil** utilizes this varying direct current in its primary to form an alternating current in its secondary. A **receiver** utilizes this alternating current in a coil of wire wound around a permanent magnet to weaken and to strengthen the magnet alternately. The magnet alternately attracts and releases an iron diaphragm, causing it to vibrate and reproduce the same sounds as originally fell upon the transmitter.

A **transformer** consists of two independent coils wound upon an iron core, which usually consists of flat strips of iron. The alternating current is passed through one coil, whereupon the other, being cut by the lines of force of the first, induces within itself an E.M.F. as many times as great as that of the first as the ratio of its coils to those of the first.

A **step-up transformer** has more secondary than primary turns and therefore has a larger secondary than primary voltage. The reverse is true of a **step-down transformer.**

Alternating current is stepped up at power houses to raise the

voltage and reduce the amperage for transmission. The pressure is reduced near the place of use by a step-down transformer.

Transformation of pressure is accomplished with little loss of energy and with great saving in transmission losses. Voltage of any magnitude can be secured for any purpose.

EXERCISES

1. What are the essential parts of any generator of electricity that converts mechanical energy into electrical energy?

2. If the field poles of a generator are at the right and left and a coil rotates horizontally between these poles, show that the induced E.M.F. must alternate in direction.

3. If there are two poles in the field magnet of a generator, how often will the direction of the E.M.F. induced in the coil reverse during one rotation? Would this be true if there were four poles in the field? Why?

4. What are slip rings? On what kind of generator would you expect to find slip rings? What electrical connection is made by slip rings?

5. Is the polarity of the slip rings constant or alternating? What kind of polarity do the brushes on the slip rings have? What kind of current should flow between the brushes?

6. A simple direct-current dynamo has a field magnet, a coil wound on a rotating iron core, commutator, and a pair of brushes. How would you connect the ends of the coil? Where would you place the brushes?

7. Is the polarity of the segments of a commutator constant or alternating?

8. Explain why the polarity of the brushes of the direct-current dynamo is not like that of the commutator segments. What kind of current flows from one brush to the other?

9. What change would be made in the commutator of a D.C. dynamo if additional coils were wound upon the armature core?

10. What change would the addition of more field poles necessitate? Illustrate.

11. How does a D.C. generator differ from an A.C. generator in the method of collecting current? In the method of supplying current to the field magnet?

12. Describe the field connection of a series-wound dynamo. Sketch the connections and state the advantages of such connection.

13. How is the field of a shunt-wound dynamo connected?

14. Sketch the connections of a compound-wound dynamo and tell why this type of winding is most commonly used.

15. Why is it harder to turn the magneto in Experiment 118 when the lamp is lighted? Relate this to what happens in a power house when the lamps in a house are turned on at night.

16. A certain dynamo may produce a current of 25 amperes at one time and one of 5 amperes at another time. Show why more energy is required to turn the moving part of the generator when the larger current is being produced.

17. Sketch the essentials of an induction coil with interrupter. Explain how an E.M.F. is induced in the secondary coil.

18. For what purposes are induction coils used? Why?

19. What is meant by self-induction? What effect does it have upon the flow of electric current in the circuits where it occurs?

20. Tell briefly the energy changes that occur in a transmitter, in the induction coil, and in the receiver of a telephone circuit.

21. In a step-up transformer, a voltmeter and an ammeter in the primary circuit indicate 2300 volts and 300 amperes respectively. With 500 turns on the primary side and 10,000 turns on the secondary, what will be the voltage and the current of the secondary, neglecting losses?

22. Make a diagram of the arrangement of generator, trans-

formers, transmission line, and a consumer's circuit, showing the customary scheme for transmission of electrical energy.

23. What effect does self-induction have upon the primary of a transformer when the secondary circuit is open? Is this effect valuable or the opposite?

24. Discuss the relative usefulness of alternating and direct current. Which is more commonly produced at present? Why?

25. For some purposes it is necessary to have a generator which can produce either kind of electricity at will. How could such a machine be constructed?

26. Alternating current for domestic use is caused to alternate 120 times per second (60 cycles). If the dynamo field has 8 poles, how many revolutions per second must be made to produce this frequency of alternation?

27. Shunt-wound generators usually have a variable resistance in the field circuit. If this variable resistance is decreased, how will the strength of the field poles be affected? How will the E.M.F. of the dynamo be changed?

28. Of what importance is the residual magnetism of the field poles of a D.C. dynamo?

29. If a dynamo is not producing enough pressure, what are the two simple things that can be done to make it do so?

30. A dynamo is causing 25 amperes to flow away from its positive brush. What becomes of this current? Does the dynamo produce electricity or does it push electricity from place to place?

31. Describe the energy transfers that take place between the boilers and the propellers of an electrically propelled ship.

32. What is the objection to placing telephone wires near alternating-current conductors?

CHAPTER XXVI

BODIES IN MOTION

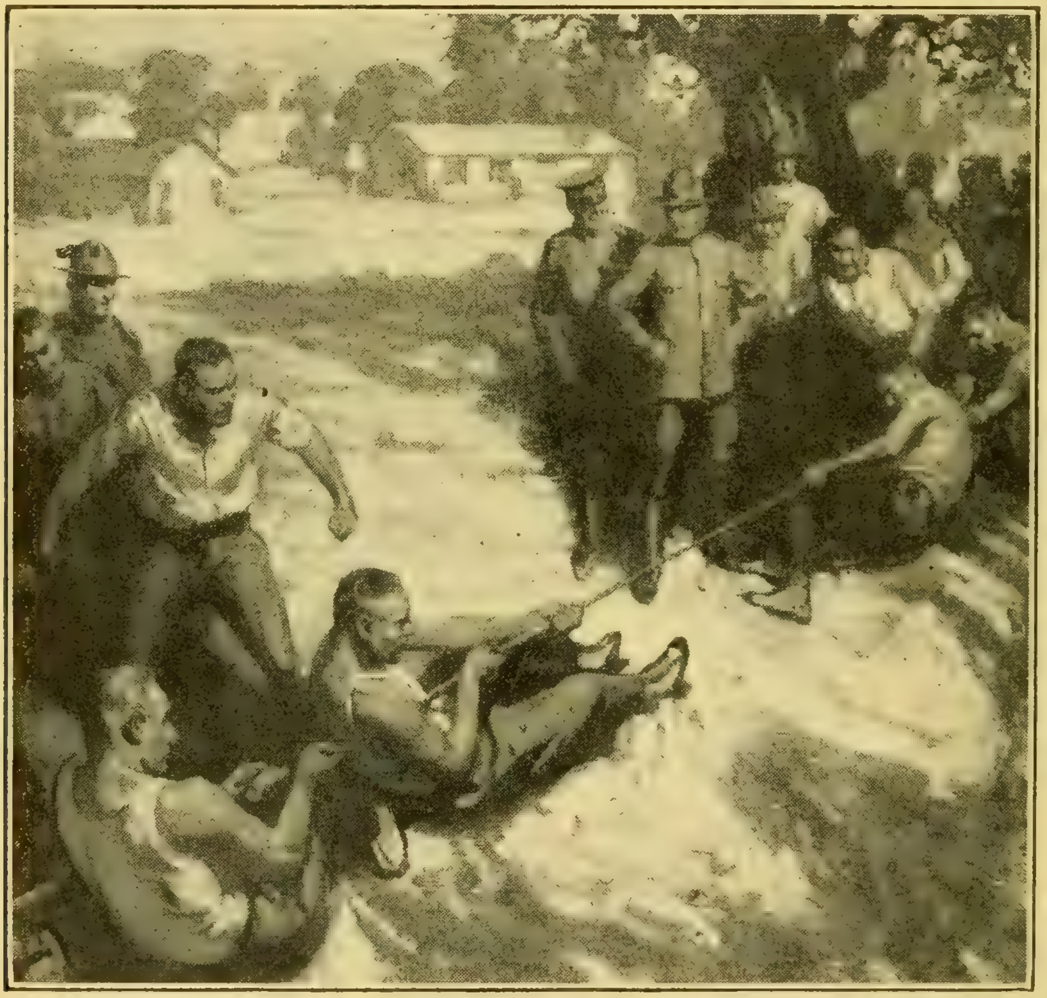
The more we study Physics, the more we realize that we knew much of it already. What we learn is often an explanation of common things not heretofore understood. Several of the following chapters treat things which people have known for centuries. Science has classified this knowledge and made it possible for people to discuss these subjects scientifically without being misunderstood.

It is easy to avoid confusion in a new science like radio, which has an exact vocabulary, limited more or less to radio specialists. But in the old science of mechanics, with its many terms common in everyday speech, the utmost care is required for accurate expression. For instance, we think of *gas* as something used for lighting or heating, but in mechanics air and steam are also gases.

So we see that in studying this old science of mechanics we must take special pains to learn the exact, scientific meanings of the words we are to use in acquiring the different laws and principles. Instruction in mechanics begins with the use of the term *force*. *A force is a push or a pull which tends to change the velocity or direction of a body's motion.* We are now ready to consider the part of Physics that deals with the action of forces upon bodies. This is the subject known as Mechanics.

328. Equilibrium. — The primary fact about forces is that they produce or prevent a change in the motion of a

body. In a tug-of-war (Figure 498) the men of each team pull to move the rope their way and to prevent the men on the other team from moving it theirs. When each team exerts the same force, neither moves the other, and the rope remains at rest. This condition, in which the two sets of



Courtesy U. S. Rubber Co.

FIGURE 498.

In a tug-of-war, equal forces in opposite directions produce stationary equilibrium.

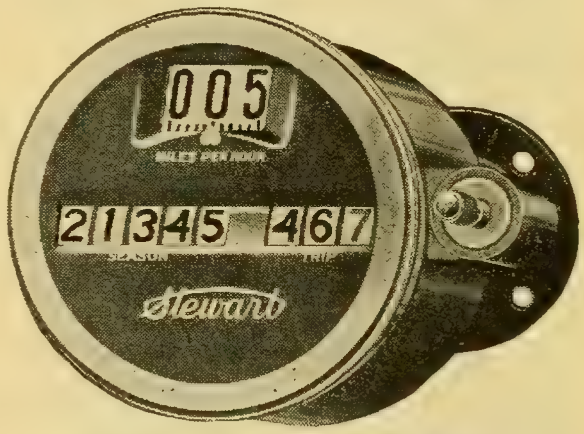
forces are equal and opposite in direction, is known as *equilibrium.* In such a case of *stationary* equilibrium, a body is at rest because all the forces acting on it are balanced, and the sum of all the forces is said to be zero.

A body in equilibrium is not necessarily at rest. A body moving with uniform speed is also in equilibrium. This is

illustrated by a steadily rising elevator. The force with which the cable is pulling up just equals the downward force of gravity. This equilibrium of a steadily moving body is called *dynamic* equilibrium.

When the elevator was starting from rest, the pull of the cable was greater than the weight of the loaded car. That is, a certain amount of the upward force was not balanced by gravity. An unbalanced force produces a change in motion and a disturbance of equilibrium.

329. Relativity of Motion. — The motion of a body is its change of position with reference to some other object. Since the motion of one body is always compared to the position of some other body that is itself in motion, it follows that all motion is relative. A man in a train moves past a man standing by the track, but is stationary with reference to a man across the aisle. A mountain is stationary with reference to an adjacent peak but, like the rest of the earth, moves with enormous speed with reference to the sun and the stars. Even the sun, the center of our unceasing revolution, is moving through space at great speed.



Courtesy Stewart Warner Speedometer Co.

FIGURE 499.

The speedometer indicates *velocity* in miles per hour.

330. Speed and Velocity. — A train moves faster than a horse; an airplane moves faster than a train. A train may have a velocity of 60 miles per hour, a sprinter may have a velocity of 10 yards per second, a bullet from a rifle may have a velocity of 3250 feet per second. In each

of these cases, the velocity is expressed as the distance the body has moved in a unit of time. We may define *velocity as the time rate of motion.* Velocity, like motion, is relative and must be compared to that of some other body. The earth is considered the stationary body for all motions on it and the velocity of bodies on the earth is determined by measuring their rates of motion with reference to the earth. We should keep in mind that the speed or the velocity of a body as expressed above does not necessarily mean that it must be maintained for the full unit of time stated. The velocity of a train may be 60 miles per hour at a given time, but it is unlikely that it will run 60 miles in any single hour at this exact speed.

331. Acceleration. — The train mentioned in the preceding paragraph may actually cover 60 miles in an hour and yet not have a velocity of 60 miles per hour (60 mi/hr) for the greater portion of the hour. What we really mean is that its average velocity is 60 mi/hr. In starting, its velocity must be much less than this figure, and this must also be true in stopping, in rounding curves, and in ascending grades. On the other hand, if it is to average 60 mi/hr, the train must run faster than this between stations, where the track is straight and there are no grades to climb. The train therefore is undergoing repeated changes in its rate of motion; its velocity is increased and decreased according to the conditions of the track. A boy coasting on a sled is subject to much the same changes in velocity (Figure 500). His rate of motion at starting is zero but at the end of the first, second, third, fourth, and fifth seconds he may have obtained velocities of 2, 4, 6, 8, and 10 ft/sec respectively. His gain per second changes to a loss per second as he comes to the bottom of the hill and slowly comes to rest on the level ground.

It is seldom, then, that a body moves with unchanging velocity. If it does move in this manner, it is said to have *uniform motion.* Most moving bodies, however, are so acted upon by unbalanced forces that *their motion is continually increasing or decreasing in velocity. Such motion is accelerated motion;* the word *accelerated* being usually employed no matter whether the velocity is decreased or increased.

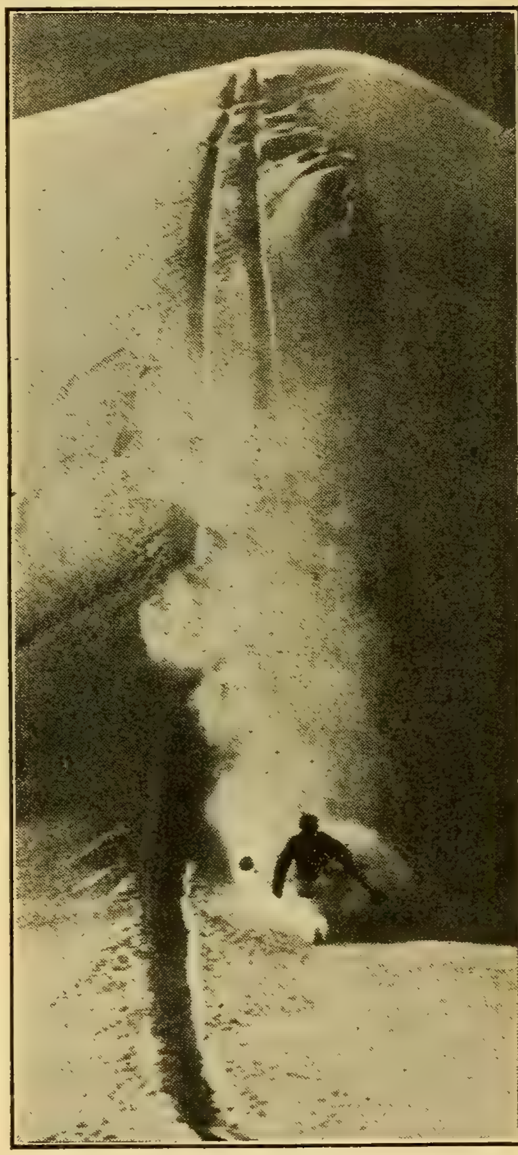


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FIGURE 500.

The velocity of the ski-jumper increases as he slides down the slope. This increase in velocity is called *acceleration.*

If the gain or loss takes place *by equal amounts in equal intervals of time,* the resulting motion is a *uniformly accelerated* motion. *The acceleration of the motion is the gain or loss in velocity in a given unit of time.* A uniform change in velocity is a uniform acceleration, and it results from a constant force being applied to the body.

332. Expressions of Acceleration. — Any expression of acceleration is necessarily an awkward expression to say or to understand. An electric train may increase its velocity by 1 mi/hr during each of the first 30 seconds after it starts. Its increase in velocity, or acceleration, is then 1 mile per hour per second. The boy coasting on the sled may have increased his velocity by 2 feet

per second during each of the first 11 seconds of his ride. His motion then is accelerated by 2 feet per second per second (usually written 2 ft/sec^2) and his velocity at the end of 11 seconds is 22 ft/sec. Thus we see that velocity is expressed in feet per second, and acceleration, or rate of

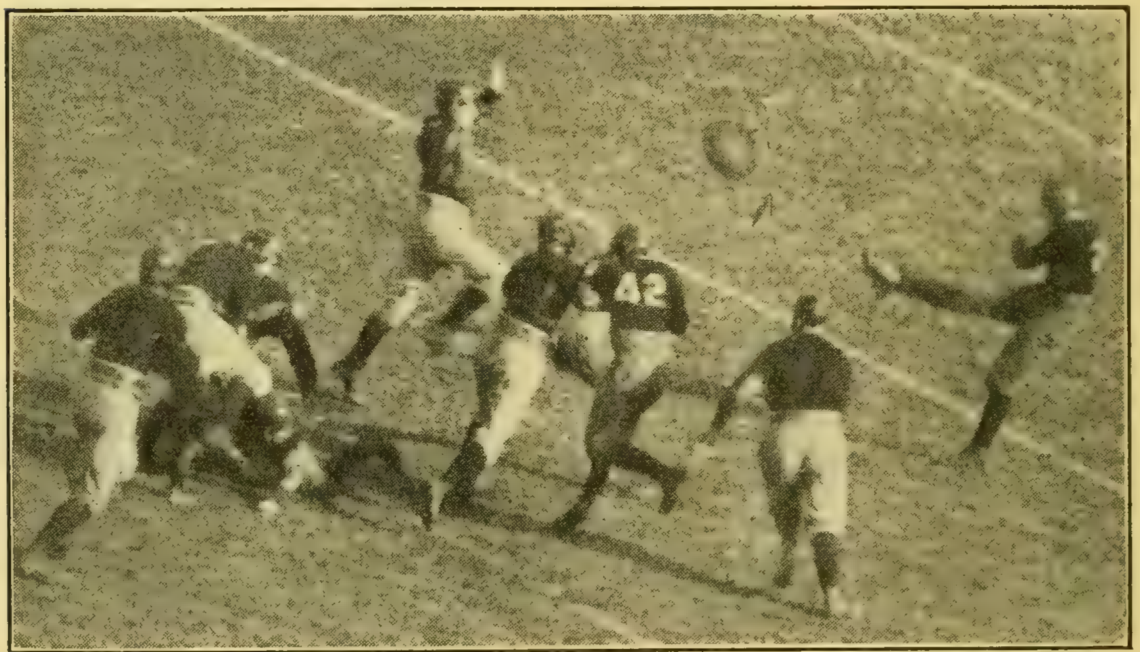


FIGURE 501.

The motion of the body is accelerated as long as the force is applied to the body. The football player keeps his foot against the ball as long as possible to give it a greater velocity.

change of velocity, must be expressed in *feet per second per second* or some equivalent form.

333. Some Accelerated Motions. — The examples of the moving train and the coasting sled indicate that all bodies moving from a state of rest pass through a state of accelerated motion before reaching a condition of uniform motion. A ball thrown by a player has an accelerated motion as long as the force of the hand is exerted against the ball. During the brief period of time when a ball is being acted upon by a ball club, tennis racket, or golf club, the ball is undergoing an acceleration and increases in speed as long as the force acts

upon it (Figure 501). As each of these moving bodies is brought to rest, it must pass through a corresponding decrease in velocity. The motion of the train is accelerated (negatively) by the brakes, the sled by friction, and the baseball by a force exerted by the fielder in stopping the ball. Every speeding up or slowing down of a moving body illustrates accelerated motion.

FIGURE 502.

The narrow stream near the bottom carries as much oil as the wide one at the top because it runs faster; it runs faster because the force of gravity has acted upon it for a longer time.

334. Acceleration Due to Gravity. — Newton is said to have observed a falling apple and from that simple fact developed the law of universal gravitation. The fall of objects when released is so common that we do not stop to think that there must be a cause for it. A pencil rolls along the table and falls when it reaches the edge. A thousand examples could be given of the tendency of bodies to travel toward the center of the earth. Moreover, we all have some knowledge of the fact that the motion resulting from this tendency to fall or slide downward is an accelerated motion. We know either instinctively or by experience that it is safe to jump from low elevations but not from high ones. Some may have experienced the accelerating effect of gravity as they coasted on sled, bicycle, or automobile down a long grade. A few may have observed that a thick liquid, like molasses or oil

(Figure 502), runs from a container in a narrowing stream because the lower part of the stream is running faster than the upper part.

335. Acceleration of Falling Bodies. — The actual value of the acceleration produced by the force of gravity can be determined easily. The true meaning of the result may, however, be better interpreted after the study of the paragraphs immediately following. This experiment simply shows one fact from which inferences may be drawn.

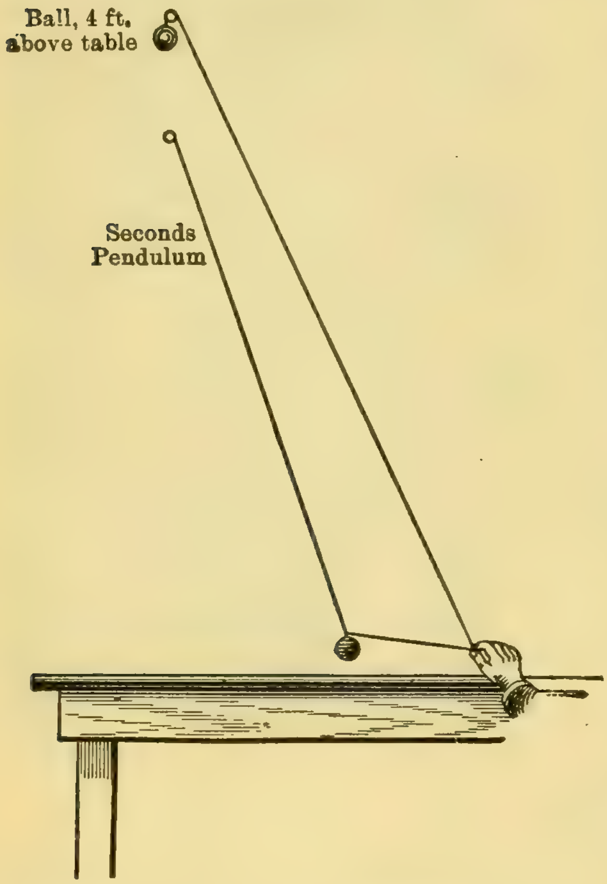
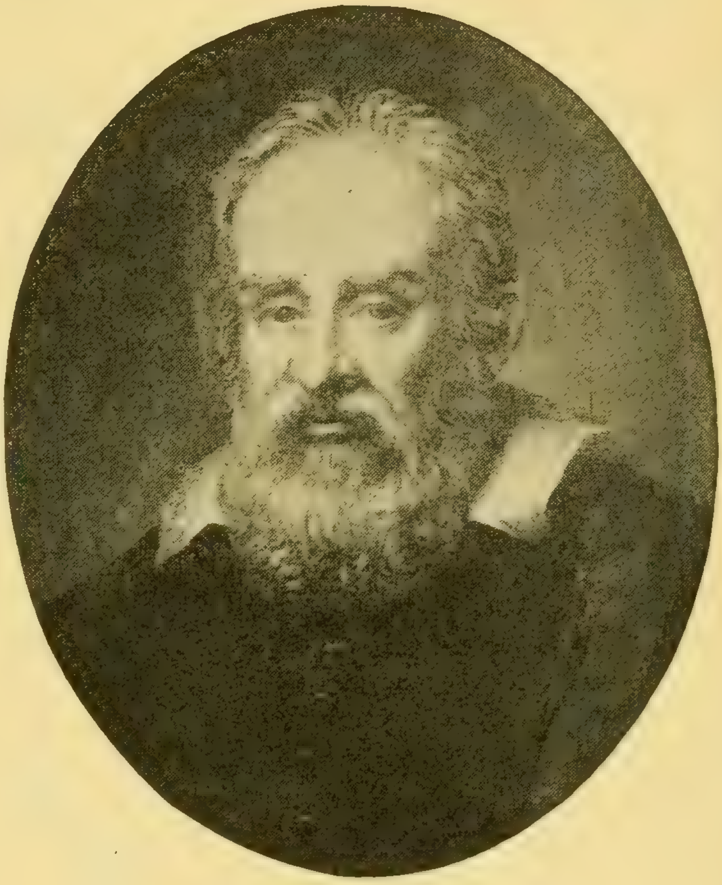


FIGURE 503. — FALLING BALL AND SWINGING PENDULUM.

EXPERIMENT 123. — A seconds pendulum is 39.1 inches long. Suspend such a pendulum so that it will swing just clear of the floor or the chalk rack. Four feet above the lowest point of the pendulum's swing, and about an inch to one side, drive a second nail (Figure 503). Tie a long silk thread to a steel ball and draw the ball to the upper nail by the thread. Draw back the pendulum by a short piece of cord, holding both the silk thread and the cord in one hand. When both are released, the ball falls and the pendulum swings. *Where is the pendulum when the ball has fallen 4 ft?*

The next paragraphs show that if a body falls 4 ft in one half second, it will fall 16 ft in one second. Moreover, if it travels 16 ft in the first second of its fall, it must have obtained a velocity of 32 ft during the first second that gravity moves it freely.



Galileo Galilei (1564–1642) is notable for his work in two widely different fields of science, astronomy and physics. He is perhaps best known for his defense of the Copernican explanation of the universe. Hearing of a telescope that had been invented in Holland, he designed and made a different one for himself. With this instrument he observed the movement of Jupiter's satellites and concluded that the planets were small bodies moving about the sun instead of about the earth as the center. His telescope proved what Copernicus and still earlier philosophers had only guessed. In physics, his work is less spectacular but even more important, his chief contributions to this science being along the line of mechanics. Modern ideas of force, motion, velocity, and acceleration originated with Galileo.

Disregarding air resistance, gravity produces an acceleration, or change of velocity, of 32 ft/sec^2. This value (32.16 ft/sec^2) changes slightly according to the location, because at the poles there is less distance and hence more attraction between bodies and the center of the earth than if the body is at the equator. Previous to the time of Galileo, it was believed that falling bodies had a motion that varied as the weight of the body. Galileo disproved this idea by a famous experiment of dropping bodies of different weights from the tower of Pisa (Figure 504) and showing that the acceleration of gravity is the same for all bodies. Later, when the air pump had been invented, it was shown that even a feather falls at the same rate in a vacuum as a coin does (Figure 505).

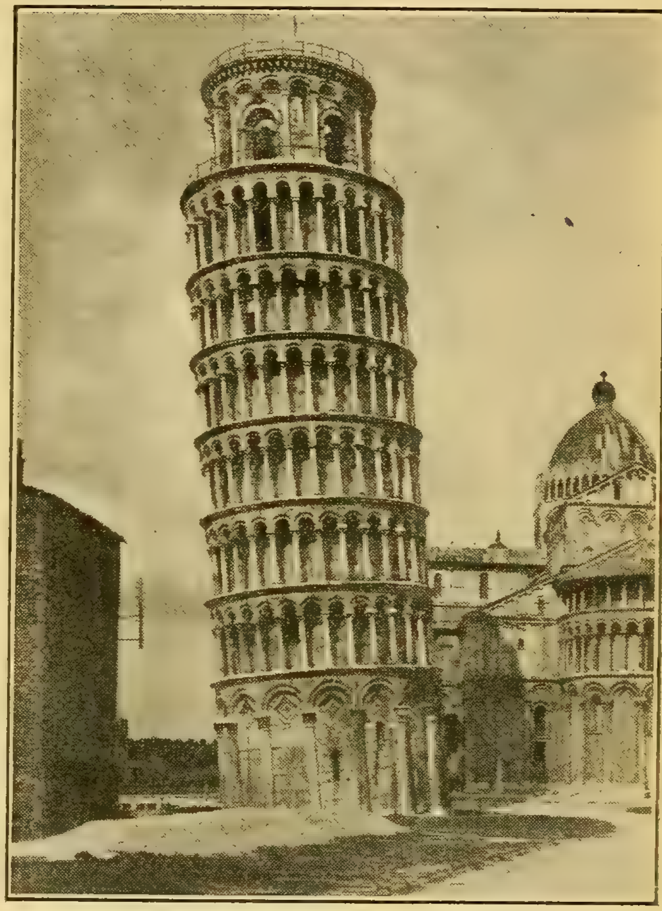


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FIGURE 504. — TOWER OF PISA.

Galileo dropped bodies of different weight from this tower and observed that except for very light objects, they all fell at the same rate.

EXPERIMENT 124. Cut a disk of heavy paper or of light cardboard just a bit smaller than a half dollar. Place the disk on the coin and drop the two flatwise to the floor. The coin prevents the air from getting under the disk and thus resisting its fall. *What is the relative speed of the two bodies?* Let the disk project over the edge of the coin and drop them. *What is the result? Why?*

336. Velocity of Uniformly Accelerated Motions. — Keeping in mind that acceleration means only a *change in velocity*, we can now see what the velocity of a body at any instant will be. A freely falling body starting at rest acquires a velocity of 32 ft/sec during the first second of its fall. Just at the end of its first second of fall its velocity will be as stated, but during the next second its velocity is increased by another 32 ft/sec, and so on for as long as the body falls without interference. During each second, the velocity is increased by the amount of the acceleration.

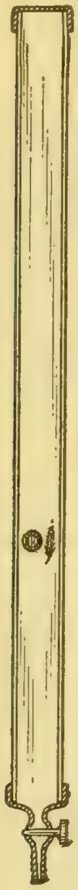

FIGURE 505.

In a vacuum, a feather and a coin fall at the same rate.

By reference to the diagram (Figure 506), it can be seen that the velocities of a freely falling body at the end of the first, second, third, fourth, fifth, and sixth seconds will be equal to **g** × **t**, where **g** is the acceleration of gravity and **t** is the time in seconds. These velocities are found to be 32, 64, 96, 128, 160, and 192 ft/sec, respectively. If the body rolls or slides down an incline, the value of its velocity at any instant is found by the equation **v** = **at**, where **a** is the acceleration of the incline. If, in Figure 507, **a** is 3 ft/sec², the velocities will be 3, 6, 9, 12, 15, and 18 ft/sec. Many bodies develop a reaction to the forces that move them, and so do not exceed a certain maximum velocity.

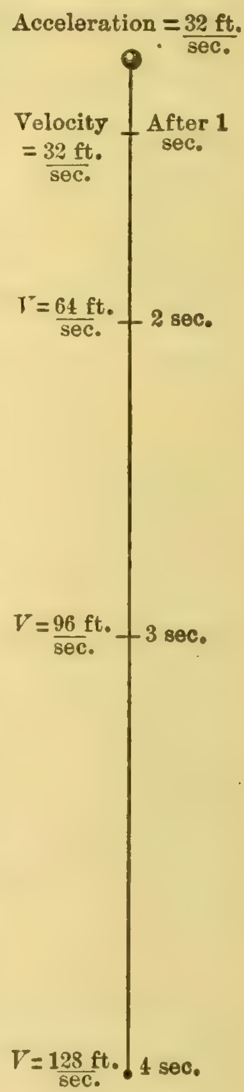

FIGURE 506.

At any instant, $V = at$.

337. Distance Covered by a Body with Accelerated Motion. — When the motion of a body is uniform, the distance the body travels in any given time can be found by multiplying the velocity by the time of travel. Thus a man walking at a uniform rate of 4 mi/hr for 3 hours travels a total distance of 4×3, or 12 miles. Or if his *average* velocity is 4 mi/hr, the distance is still the same. But when his

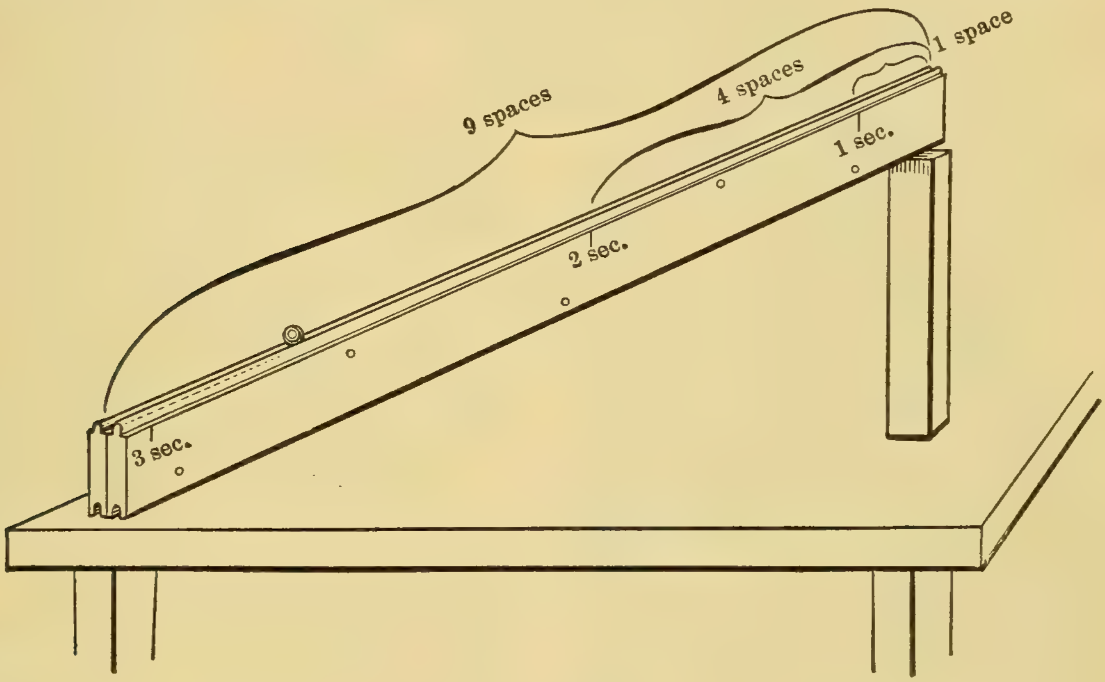

FIGURE 507.

The total distance passed over by a uniformly accelerated body is proportional to the square of the total time.

motion is uniformly accelerated instead of uniform, there must be some other method of determining the distance traversed during a known period of time. The basis of this method may be learned by an experiment. Of many forms of apparatus, the most common type reduces the acceleration of gravity by causing a body to roll down an incline instead of falling freely. This enables us to measure the small distances traveled during a second.

EXPERIMENT 125. — Select two straight matched boards and nail them together side by side so that there is a groove between the tongues

(Figure 507). Let one observer watch the swings of a seconds pendulum and tap the table each time the pendulum swings past its lowest point. Let another observer release a steel ball at one tap and with a piece of chalk mark the position of the ball on the plane at each of the next three or four taps. After a few trials considerable accuracy is possible. An examination of the result shows that the total spaces *counted each time from the beginning* are in the ratio of 1 : 4 : 9 : 16.

Galileo tried this experiment in much the same form except that due to the absence of modern clocks, he timed his trials by a water clock. His results puzzled him until finally he explained them in this way: If a body is acted on by gravity for two seconds instead of for one, it will acquire a *final* velocity twice as great as in one second. Its *average* velocity is therefore doubled and it will travel four times as far in *two* seconds (not *during the second second*) as it will travel in one, because it travels *twice as fast* and *twice as long.* In three seconds the body with uniformly accelerated motion will acquire three times the average velocity obtained in one second and will be moving three times as long; its distance covered will be 9 times that of the first second. A continuance of this explanation gives 16, 25, 36, and so on, for the spaces covered during four, five, and six seconds. This means that the spaces traversed by an accelerated body vary as the *square* of the number of time units of travel; and this relation does not depend on the amount of acceleration.

338. Equation for Falling Bodies. — After **t** seconds, a falling body obtains a *final* velocity of **at**, or an *average* velocity of $\frac{1}{2}$ **at**. But *distance* = average velocity × time, or: $S = \frac{1}{2}at \times t = \frac{1}{2}at^2$. This equation conforms with the previous paragraph. Figure 508 shows the distances covered by a freely falling body. This figure shows the *cumulative* effect of a constant force upon the movement of bodies set in motion by it.

A ball thrown upward is subjected to this force and is *negatively* accelerated. This negative acceleration reduces the upward velocity of each body by 32 ft/sec. After being brought to rest, the ball begins to gain speed downward at this rate. One half of the time that the ball is in the air is spent in going up, and the speed on leaving the hand is the same as that with which it strikes when caught on its return.

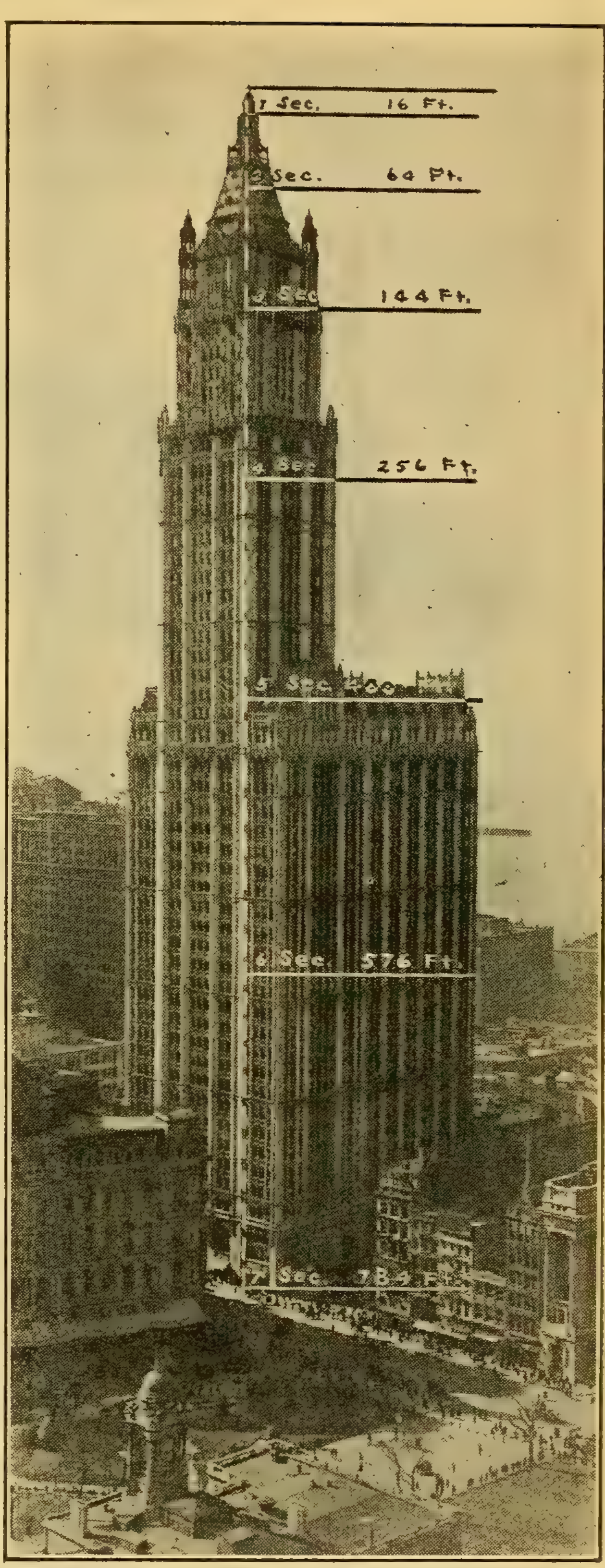

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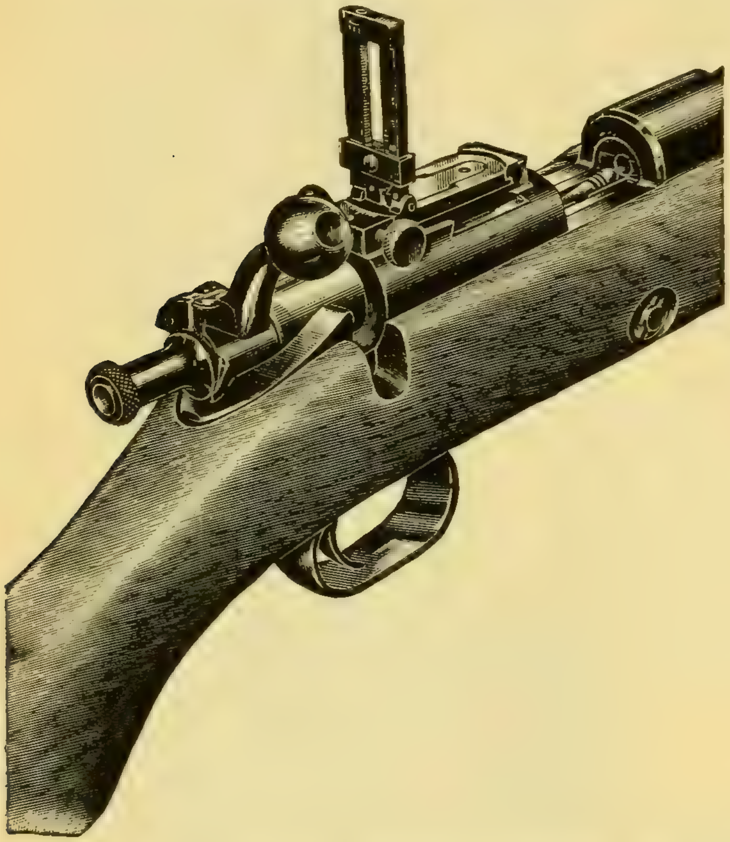
FIGURE 508.

A ball would fall to the ground from the top of the Woolworth tower in about 7 seconds. The distances increase in proportion to the square of the time during which the body falls.

339. Projectiles.—Rifles are sighted (Figure 509) so as to allow for the dropping of the bullet in its flight. Cannon whose projectiles travel long distances are pointed several degrees above the horizontal so that gravity will not bring the projectile to earth too soon. The maximum range is secured by pointing the gun at an angle of about 45°. Allowance is unconsciously

made for gravity in all games in which a ball is thrown or batted through the air. The path of all such bodies is a curve whose sharpness depends upon the relative magnitude of gravity and of the other force impelling the body forward.



Courtesy Winchester Repeating Arms Co.

FIGURE 509.

Sighting through the elevated rear sight of a rifle raises the muzzle of the gun and makes allowance for the fall of the bullet during flight.

340. Effect of Air Resistance. — We have spoken little of the effect of air resistance on falling bodies. Light falling bodies, as paper, leaves, and thistledown, quickly obtain such a speed that air resistance counterbalances the accelerating effect of gravity. Heavier bodies, as raindrops, increase their speed as they fall until the resistance of the air neutralizes the tendency of gravity to increase their speed. When air resistance and gravity are balanced, the body is no longer moving with accelerated motion but with uniform motion.

QUESTIONS

1. Define equilibrium. Give examples of bodies in stationary equilibrium and in dynamic equilibrium.

2. Define motion. What is meant by the statement that all motion is relative?

3. Give three examples of the units in which velocity is expressed. What is the difference between average velocity and uniform velocity?

4. Distinguish between velocity and acceleration. Give two examples of the proper use of each word.

5. A boy coasting travels at the rate of 3, 6, 9, and 12 ft/sec at the end of the 1st, 2d, 3d, and 4th seconds of his ride. What is his change in velocity? What is his acceleration?

6. Give three examples of uniform motion and three examples of uniformly accelerated motion.

7. What is gravity? What effects of gravity are matters of common observation?

8. Is gravity a constant or an impulsive force? What kind of motion will be given to bodies upon which gravity acts without opposition?

9. A boy coasts with uniformly accelerated motion. If he travels a foot during the first second, how far will he travel in 2 seconds? In 3 seconds? In 4 seconds?

10. In the previous question, what relation exists between the distance of his travel and the time of his travel. Give another illustration of your meaning, using simple numbers.

11. What is the gravity acceleration of a freely falling body in English units? In metric units? What does your answer mean?

12. What will be the velocity of a freely falling body after one second? Is the number of feet the body falls in one second the same as the velocity it acquires in feet per second?

13. After how long a fall is the velocity of a body 64 ft/sec? For how long a time will its velocity be 64 ft/sec?

14. A boy drops a ball from a window. What is the velocity of the ball as he releases it? After one second? What is the average velocity during the second? How far will it fall during the second?

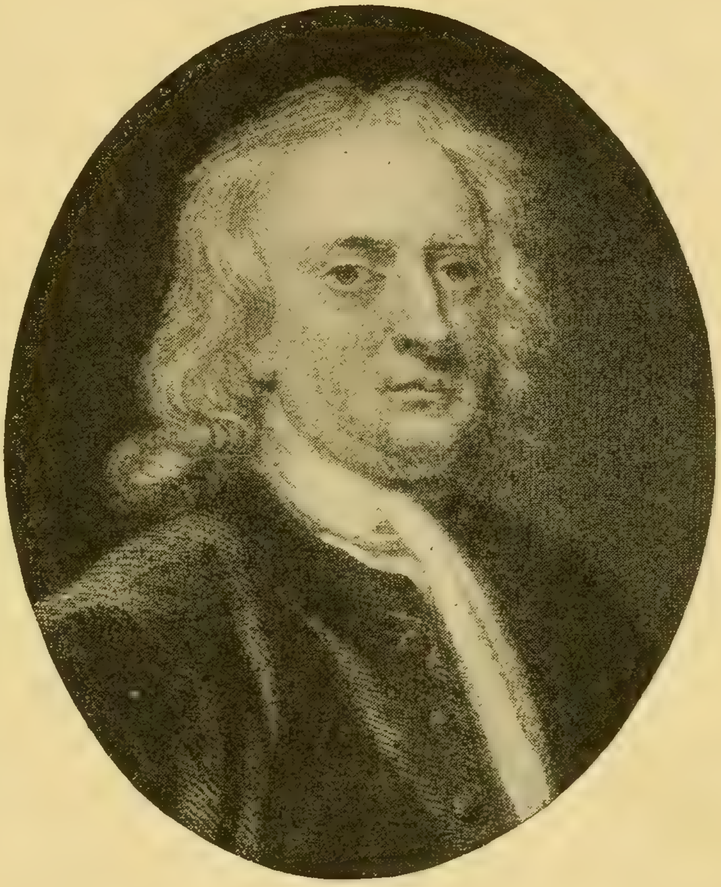
15. Compare the acceleration of a ball on a horizontal plane with that on an inclined plane and with that on a vertical plane.

341. Newton's Laws of Motion. — It is of constant interest to note the beginnings of physical ideas that are now commonplace. It is hard to realize that not long ago, most of the things now in our physics books had either not been

thought of, or else were just beginning to be understood. The great names in physics are those of men who have made clear statements about the behavior of ordinary things around us. Thus Newton did not search out and discover hidden or mysterious things; he simply put in clear language a number of relations that had not been previously expressed. These relations, or laws as they are called, deal with the behavior of forces on bodies. Since forces are the cause of motion, these laws are called the *laws of motion*. Some of them can be verified by experiment; one is so simple as to be an axiom, while another is simply a statement of belief. The three laws are identified by number and by name.

342. The First Law: Inertia. — A chair on the floor and a book on the table remain where they are placed until a force acts on them to move them. It needs no proof to show that all objects at rest remain at rest until acted upon by an external force.

On the other hand, moving objects do not come to rest of their own accord, although they may appear to do so. Many moving bodies, such as a ball rolling on a smooth pavement, are brought to rest by frictional forces. By reducing friction, their motion can be maintained longer, hence we may *infer* that if all external forces were done away with the ball would continue to roll forever in a straight line without loss of speed. This inference cannot be proved, but the earth does continue to move at uniform speed because no considerable forces act upon it to retard its motion. The tendency of a body to continue in motion is evident to one who notes that an automobile or a train moves for some distance even when brakes are used to check this motion. The inertia of a moving baseball has to be overcome by the person catching it. Sudden changes in the speed or direction of a



Isaac Newton (1642–1727) probably has no superior as a physicist and mathematician. A complete record of his researches, observations, and conclusions would fill many volumes. In elementary physics, he is probably best remembered for his conception of the idea that white light is a composite of the different primary colors; for his law of universal gravitation by which he explained the motions of the heavenly bodies; and for his laws of motion. As a mathematician, Newton devised the method of differential calculus.

moving train cause a standing person to lurch forward, backward, or sidewise as a result of the tendency to retain the previous condition of motion. The inertia of moving bodies is utilized in the hammer and in the pile-driver.

Newton's first law summed up this tendency of bodies to persist in any condition of motion, that is, to possess inertia. *A body at rest remains at rest and a body in motion remains in motion in a straight line with undiminished speed, unless acted upon by an external force.*

343. The Second Law: Momentum. — To throw a ball at a certain speed requires a certain force, and to throw a ball with twice the speed necessitates twice the force. A boy kicking a football uses less force than a 'varsity fullback and hence produces less change in the motion of the ball. Every moving body depends for its motion upon the force that set it in motion; the quantity of its motion is an indication of the amount of force used to move it. We use the word *momentum* to express *quantity of motion*, and *momentum is calculated by multiplying the mass of a body by its velocity.*

The second law asserts that *every force acting upon a body changes the momentum of the body by an amount proportional to the magnitude of the force and to the time that it acts.* That is, if a one-pound force produces a certain change of momentum, a two-pound force acting upon the same body for the same time produces twice the change in momentum. The second law may be demonstrated by the following experiment.

Experiment 126. — Place an easily moving car, containing a 100-gram weight on an inclined plane with slant enough to allow gravity to overcome the slight friction of the car. Attach a long paper tape to this car and pass the tape over a flanged pulley at the end of the plane (Figure 510). Below the pulley fasten a 100-gram weight to the tape. Mount a pendulum with an inked brush just ahead of the pulley so that, as it

swings, it will mark the tape. Release the car and pendulum simultaneously and obtain a record on the tape of the spaces passed over during each successive swing of the pendulum. These spaces are in the ratio of 1 : 3 : 5 : 7, etc. *Does this show increased velocity? Does it show increased momentum?* Now take the 100-gram weight from the car and add it to the falling weight. This doubles the moving force without changing the mass. A record, taken now, shows that each space on the tape is double the corresponding space in the previous trial. *How has velocity changed when force is doubled? What change in momentum?*

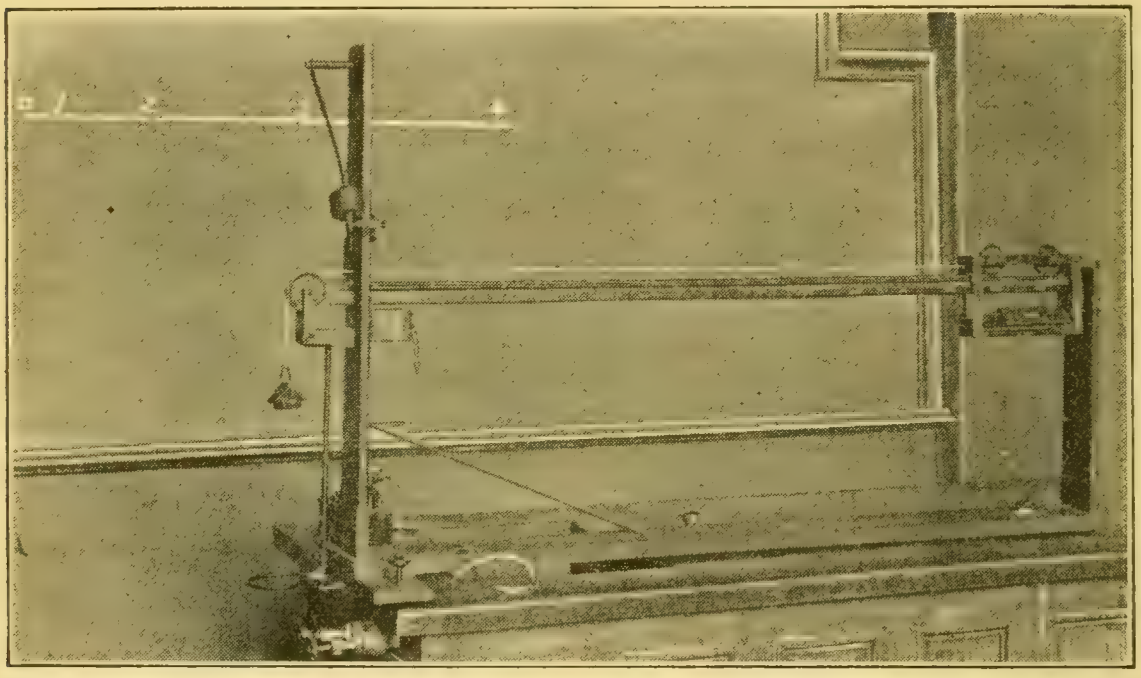


FIGURE 510. — ACCELERATED MOTION MACHINE.

The paper tape is stretched from the car over the pulley to the weight. When the pendulum swings across the tape, it releases the car. The line on the blackboard shows the appearance of the paper strip.

This experiment shows, then, that increasing either the *force* applied or the *time* that the force acts increases the momentum of the mass moved by it.

344. The Second Law Applied. — The second law finds an application whenever a force changes the motion of a body. The velocity and hence the momentum of a tennis ball, baseball, rifle bullet, or falling weight change at a rate depending upon the force applied to set the body in motion. To " follow through " in a tennis or a golf stroke applies the

second law (see Figure 501, page 564). The ball is given a greater momentum because the force is applied to it for a longer time.

A consideration of the second law shows why all bodies fall at the same rate regardless of weight. Gravity exerts a 1-pound force on a 1-pound mass and gives the mass an acceleration of 32 ft/sec². A mass of 5 lbs is acted on by a 5-pound force. Since the inertia of the second body is five times as great as the first and the moving force applied to it is five times as great, the acceleration is still 32 ft/sec².

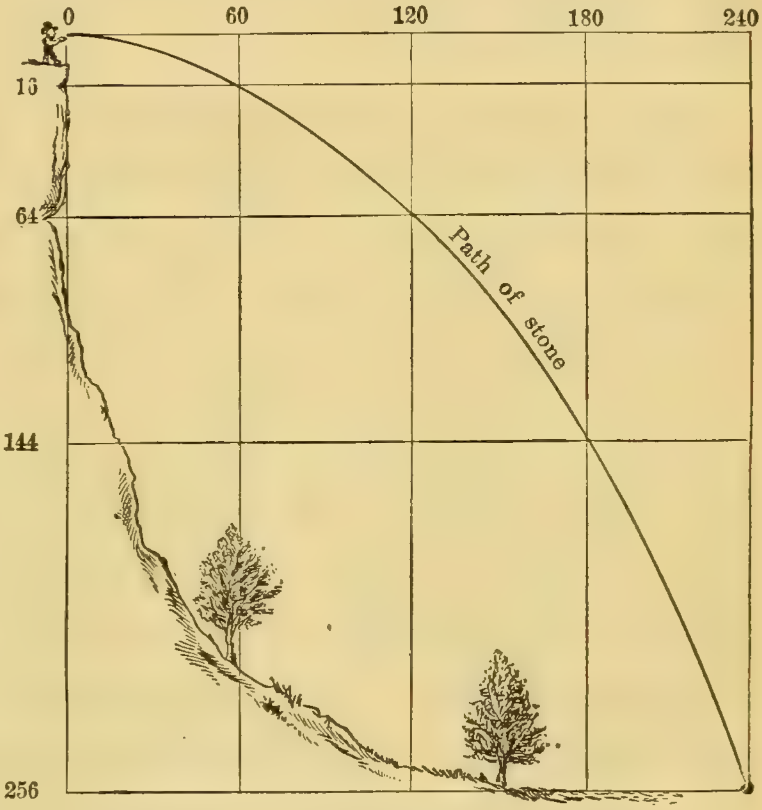


FIGURE 511.

The outward motion of the stone is constant, the downward motion is accelerated like that of any falling body. The stone falls as fast as though it were falling straight down.

An inference from the second law is that the effect of each force is independent of all other forces acting on the same body (Figure 511). This explains the necessity of sighting a rifle so that it really points at some distance above the mark. No matter how swiftly the bullet moves, gravity gives it an acceleration of 32 ft/sec² downward. A rifle bullet traveling 3000 ft/sec falls 16 ft (§ 335) during a forward motion of 3000 ft, and the rifle must be elevated to allow for this fall. A bullet dropped from an elevation of

16 ft would reach the ground at the same time as one shot horizontally from the same height. This may be verified by holding a piece of crayon loosely near the edge of a table and snapping a similar piece against it with the other hand. The first piece flies off at some distance but the second one falls straight to the floor, both reaching the floor at the same time.

345. Absolute and Gravity Force Units. — The units of force customarily used are the *pound* and the *gram*. These forces are the measure of the attraction between the earth and a pound or a gram of mass. This attraction varies somewhat as the distance of the mass from the earth's center changes. Thus the pull between the earth and a pound-mass, *i.e.* a pound-force, is greater at the poles than at the equator, since the distance between the centers of the earth and the pound mass is about 13 miles less at the poles. Although this variation is inconsequential in ordinary measurement, it is desirable at times to use a unit which is independent of gravity. Such units are called absolute units, and the English unit is derived by assigning a value to the force *required to give a pound-mass an acceleration of 1 ft/sec^2*. This unit is the *poundal*. A pound-force gives a pound-mass an acceleration of 32 ft/sec^2. A poundal, by definition, gives a pound-mass an acceleration of 1 ft/sec^2. The pound-force is therefore approximately equal to 32 poundals, but this relation is not a fixed one since the pound-force varies in value. The corresponding metric unit is the *dyne*. The dyne is the force which will give an acceleration of 1 cm/sec^2 to a gram-mass. The gram-force is approximately equal to 980 dynes, the metric equivalent of 32 ft/sec^2 being 980 cm/sec^2. A dyne is then approximately a thousandth of a gram, or one milligram.

346. Measurement of Force. — If a force does make a change in the momentum of a body, this change will be proportional to the force; or a force may be measured by observing the effect produced by it. If a force **F** acts for **t** seconds on a mass **m**, the force gives **m** a velocity of **v** or:

$$\underset{\text{(impulse)}}{\text{force} \times \text{time}} = \underset{\text{(momentum)}}{\text{mass} \times \text{velocity}}.$$

That is, $\mathbf{Ft} = \mathbf{mv}$.

Then $\mathbf{F} = \dfrac{\mathbf{mv}}{\mathbf{t}}$.

But $\dfrac{\mathbf{v}}{\mathbf{t}} = \mathbf{a}$ (§ 336).

So $\mathbf{F} = \mathbf{ma}$.

F will be in poundals when **m** is in pounds and **a** in ft/sec^2; **F** will be in dynes when **m** is in grams and **a** in cm/sec^2.

347. Solution of Force Problems. — The solution of problems involving the force equation is not difficult if we remember the units in which the various quantities are expressed. Suppose it is desired to determine the force required to give a velocity of 100 ft/sec to a baseball weighing 5 oz, when the force acts on the ball for 0.1 sec. In this case, **m** is $\frac{5}{16}$ lb; **v** is 100 ft/sec; and **t** is 0.1 sec.

$$\mathbf{F} = \frac{\mathbf{mv}}{\mathbf{t}} = \frac{\frac{5}{16} \times 100}{0.1} = 312.5 \text{ poundals};$$

or: since there are about 32 poundals to one pound-force, the force expressed in pounds is $\dfrac{312.5}{32} = 9.7$ pounds-force.

An automobile engine exerts a force of 250 pounds in starting the car. If the car weighs 4000 pounds, what will be the acceleration of the car? What will be the velocity of the car after 15 seconds?

SOLUTION: A force of 250 lbs is equivalent to

$250 \times 32 = 8000$ poundals.

$8000 = 4000\ \mathbf{a}.$

$\mathbf{a} = 2\ \text{ft/sec}^2$, the acceleration of the car.

Since $\mathbf{v} = \mathbf{at}$, $\mathbf{v} = 2 \times 15 = 30$ ft/sec, the velocity after 15 sec.

If a 50-gram weight and a 48-gram weight are hung on opposite sides of a pulley, the difference of the weights, 2 g, is the force that sets the weights in motion. But 2 g is the equivalent of $2 \times 980 = 1960$ dynes. The mass to be moved is 50 g + 48 g = 98 g. The acceleration of the weights is, then, found by

$$\mathbf{a} = \frac{\mathbf{F}}{\mathbf{m}} = \frac{1960}{98} = 20\ \text{cm/sec}^2.$$

The velocity may be determined by the equation $\mathbf{v} = \mathbf{at}$. This method furnishes a convenient way of studying accelerated motion, because the acceleration is so greatly reduced.

348. The Third Law: Reaction. — If you push hard against a heavy box, you naturally incline your body to an oblique position in order that you may exert a greater force against the box. You do not fall forward because the box supports you. The support, or the back push of the box against you, is called a *reaction.* We find that one body never exerts a force upon another one without the second reacting against the first. Our commonest movements depend upon our being able to obtain this reaction.

349. Applications of the Third Law. — We walk only because we can push backward upon the earth as hard as it pushes us forward. On smooth ice it is so difficult to obtain this reaction that it is hard to run or walk. To push a heavy object, we brace our feet against the floor and push on the floor in a direction opposite that in which the object is to be

moved. The exploding powder in a gun barrel shoots the gun backward with the same momentum as it shoots the bullet forward, the velocities of the gun and bullet being inversely proportional to their masses. The reaction, or "kick," of large guns is taken up by springs or other-

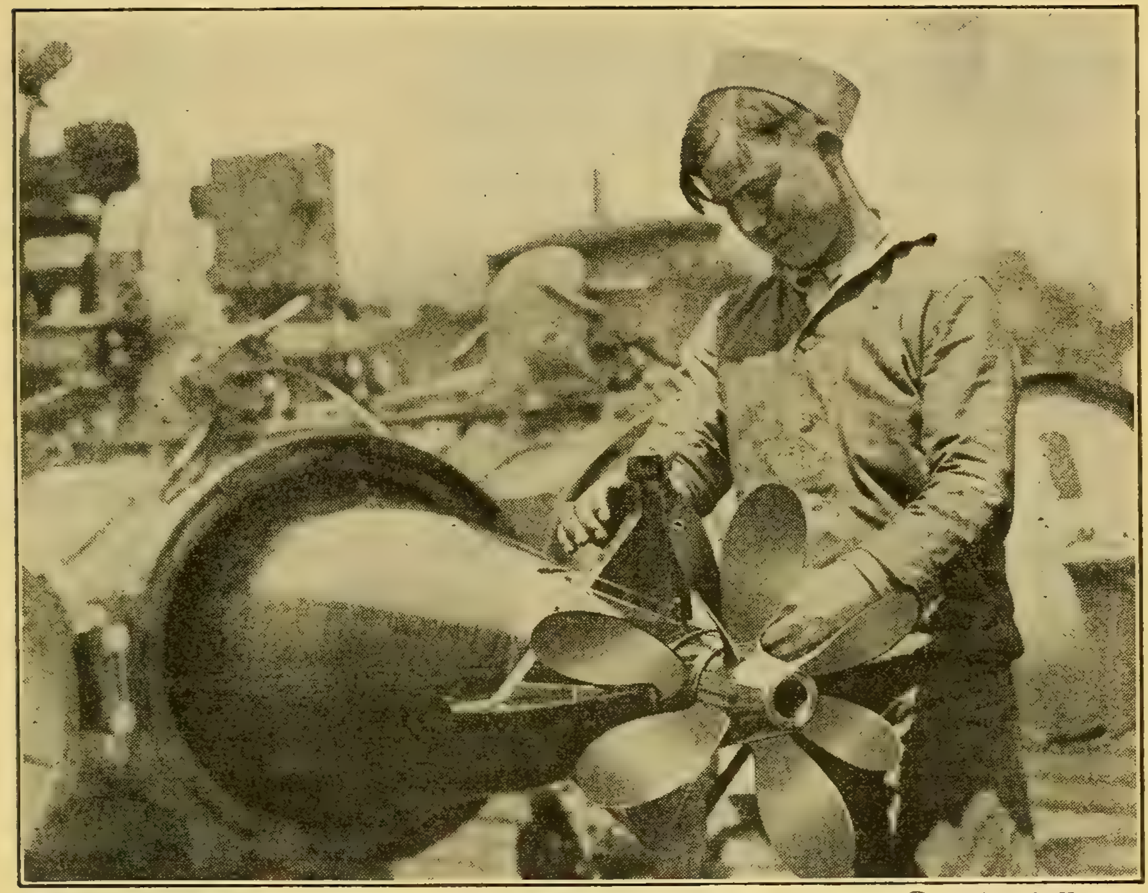


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FIGURE 512. — TORPEDO.

The two propellers, rotating oppositely, prevent the smoothly-polished torpedo from turning in the water without forward motion. How is reaction involved?

wise. A whirling propeller pushes water or air backward and the reaction of the fluid moves the motor boat or airplane forward. Torpedoes are equipped with two propellers (Figure 512), rotating in opposite directions, so that the reaction of a single one may not cause the torpedo itself to revolve in the water without forward motion. A man cannot lift himself by pulling up on his chair seat because he must

push down on the chair as hard as he pulls up. Action is on one body, the reaction on another.

Many reactions occur against the earth, which because of its great mass is not noticeably moved. One might imagine himself living on a planet a few feet in diameter, which would be spun around in one direction as he walked in the other.

We observe, then, that the operation of forces in pairs is universal; that no force can be exerted unless an equal and opposite force is exerted against it by another body. We may therefore state as the *Third Law of Motion: To every action there is an equal and opposite reaction.*

350. Experiments Illustrating the Third Law. — A number of simple experiments may be performed to illustrate the Third Law of Motion. From this number a few are shown for stationary and for moving bodies.

Experiment 127. — Hook two spring balances together and, holding one yourself, let another person take the other. Instruct the other person to pull hard on the balance, and at the same time let your own balance move toward him without opposition on your part. *How hard is he able to pull when there is no opposing force? When the reaction to a force is zero, what must the force be?*

Experiment 128. — Attach a spring balance to any stationary fixture in the room and pull until the scale reads 20 lbs. Now interpose a second scale between the first scale and the fixture and pull until the scale again reads 20 lbs. *Does the other scale read 20 lbs also? Are you pulling harder than before?* The second scale indicates the reaction of the fixture to the force of your pull. *How does the reaction compare with the original force?* Suppose you hooked a dozen spring scales together in a line and pulled until the first one registered 20 lbs. *What would the others indicate? Would you be pulling 20 or 240 lbs.?*

Experiment 129. — Squeeze a soft rubber ball between a board and the table (Figure 513). *What force keeps the board from reaching the table? What force flattens the ball on the top? What force flattens the ball on the bottom? Is the ball equally flattened on top and bottom? Why?*

Experiment 130.—There is a reaction to every force that sets a body in motion and this reaction may be shown as follows: Hang a loop of rope from the hook of a spring scale reading up to 100 lbs. Suspend the scale from a strong support and put one end of a board in the loop, the other end resting on the floor. Let a boy walk up the board until he extends the spring scale about one half of its full reading. Note the reading and then have the boy jump up from the board as high as he can. *Does the scale read more or less as he jumps? Is force required to raise the boy? What force in addition to the boy's weight is indicated by the scale?* When the boy lands on the board, the board pushes up against him to stop him. *What is the reaction to this force and what is its direction?*

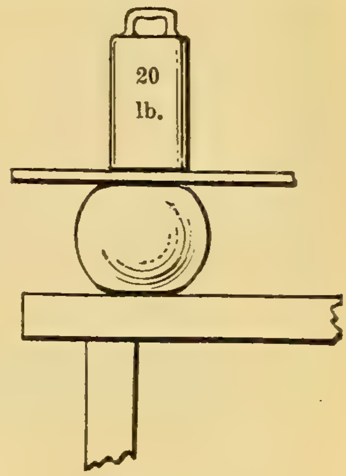

Figure 513.

Experiment 131 shows a somewhat similar application of the Third Law. Set a heavy roller spinning in its frame and place it upon the upturned wheels of a "frictionless" car such as is used for inclined-plane experiments. *What happens to the wheels of the car? Why? Why does the roller not move off the wheels?* Set the roller spinning again and place it upon the table. *Why does it move across the table?*

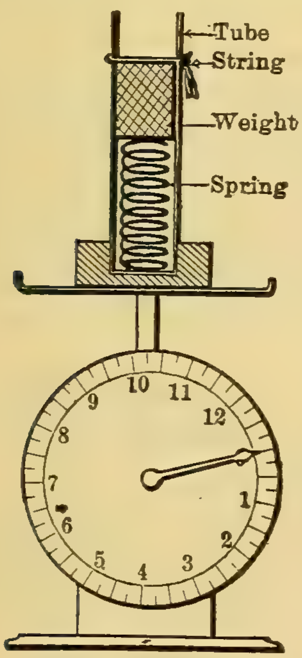

Figure 514.

Experiment 132. — Mount a pipe vertically in a wood base and insert in the pipe a coiled spring which fits easily in it (Figure 514). Compress the spring by forcing a weight down into the tube against the spring. Pass a cord through holes above the weight and tie the string so that the weight is made to hold the spring compressed. Place the apparatus upon a diet scale or a household scale (Figure 213) and release the weight and spring by burning the cord. *What forces act when the cord is burned? What force is indicated by the scale? What name is applied to this force by users of firearms?*

351. Recapitulation. — A brief summary of the preceding paragraphs indicates the following main points:

1. That an unbalanced force is necessary to change the motion of a body. 2. That this force produces a change in

the momentum in the body proportional to the magnitude of the force and to the time during which the force acts. 3. That the force is measured by the mass it moves × the acceleration given to the mass. 4. That the effect of each force is independent of the operation of other forces on the same body. 5. That the velocity acquired by a body is equal to the acceleration × the time during which the unbalanced force acts. 6. That the distance traversed by a uniformly accelerated body is equal to $\frac{1}{2}$ the acceleration × the square of the time. 7. That every action is attended by an equal and opposite reaction.

QUESTIONS

1. What is Newton's First Law of Motion? Give examples of its application to stationary bodies and to moving bodies.

2. What is momentum? How can the momentum of a body be calculated?

3. A force of 6 lbs acts on a mass of 12 lbs for a second and then on a mass of 24 lbs for a second. Compare the momenta of the two bodies. Compare the accelerations of the two masses.

4. A force of 6 lbs acts on a mass of 12 lbs for a second. A force of 12 lbs acts on a mass of 12 lbs for a second. Compare the momenta of the two masses. Compare their accelerations.

5. A force of 6 lbs acts on a mass of 12 lbs for one second. Another force of 6 lbs acts on another mass of 12 lbs for 2 seconds. Compare the momenta and the accelerations of the two masses.

6. A force of 6 lbs acts for 5 sec on a 12-pound mass. How long must a 3-pound force act on the same mass to give it an equal velocity?

7. How does the magnitude of the force used in moving a body affect the momentum of the body? How does the length of time during which the force acts affect the momentum of the body?

8. A certain force gives an acceleration to a given mass. What relation exists between the force, the mass, and the acceleration?

9. If you want to push an automobile along the street, will you need to exert a large force or a small one? For an instant or for a considerable time? What authority have you for your answer?

10. A bullet or shell is accelerated as long as the expansion of the exploded powder can push against it. Should a rifle or cannon have a long or short barrel for a long range?

11. Compare the force and the duration of its application in "bunting" a baseball with that in batting a home run.

12. What is the difference between a pound of force and a poundal? Between a gram of force and a dyne? Which of these units are constant in value?

13. State the Third Law of Motion. Show how it is applied in walking; in moving heavy objects; in the movement of trains.

14. If you hook two spring balances together and pull until each indicates 2000 grams, how hard are you pulling?

15. Why are so many reactions unnoticed? Why are reactions more noticeable on a rowboat than on an ocean steamship?

SUMMARY

A body is in **equilibrium** when all the forces acting on it counteract each other. The sum of these forces is said to be equal to zero. A body moving with uniform motion is in equilibrium. A body in equilibrium may be disturbed from that condition by any force acting upon the body.

Motion is the change of position of a body with reference to some other object.

Velocity is the time rate of motion. **Velocity is expressed** in space units per unit of time, as feet per second, miles per hour, or centimeters per second.

Acceleration is the rate of change of velocity. **Acceleration is expressed** in units of velocity per unit of time, as feet per second per second, centimeters per second per second. **Uniformly accelerated motion** results from the continuous action of unbalanced forces.

The velocity at any given instant of any body possessing uniformly accelerated motion is the product of the acceleration $\times$ the time during which the motion has been accelerated: $\mathbf{v} = \mathbf{at}$.

The distance traversed by a body with accelerated motion, if it starts from rest is: $\mathbf{s} = \frac{1}{2}\,\mathbf{at^2}$.

The attraction between the earth and bodies near its surface is a constant force and therefore produces an accelerated motion in bodies that are free to fall. The acceleration given to the motion of these **freely falling** bodies is about 32 ft/sec², or about 980 cm/sec².

Newton's Laws of Motion state that:

1. An unbalanced force is required to change the motion of a body.

2. This force produces a change in the momentum of the body proportional to the magnitude of the force and the time during which the force acts. **Thus a force may be measured** by the mass it moves $\times$ the acceleration given to the mass or: $\mathbf{F} = \mathbf{ma}$. The effect of one force is independent of the operation of other forces on the same body.

3. Every action is attended by an equal and opposite reaction.

EXERCISES

1. How can the velocity at any instant in the motion of a uniformly accelerated body be determined? Illustrate by a simple numerical problem.

2. What is the velocity of a freely falling body after 3 seconds of fall? After 7 seconds? After 12 seconds?

3. A stone is dropped from a high bridge. After 1 second where will it be, and how fast will it be traveling? After 4 seconds what will be the distance traversed and the velocity?

4. An inclined plane gives a ball an acceleration of 12 ft/sec². A ball rolls down this inclined plane in 5 seconds. What is its final velocity? What is its average velocity? What is the distance traveled by the ball in 5 seconds?

5. A train, moving with uniformly accelerated motion, travels 50 ft in the first 5 seconds. What is its acceleration in ft/sec^2? In miles per hour per second? What is its velocity at the end of 5 seconds?

6. An automobile moving at the rate of 30 ft/sec is stopped by the brakes in 3 seconds. What negative acceleration do the brakes produce in ft/sec^2 and in miles per hour per second? How far will the car move before coming to rest?

7. A boy drops a ball and catches it after $\frac{1}{4}$ second. How far had the ball dropped?

8. A ball is thrown vertically upward with a velocity of 80 ft/sec. How long will it rise? How far will it rise? How long will it take to reach the thrower? What will be its velocity when it reaches the thrower?

9. A ball is dropped from the top of a building 400 ft high. How long will it take to reach the earth? What will be its velocity when it reaches the earth?

10. An arrow is shot vertically upward with a velocity of 160 ft/sec. How long will it rise? Where will it be after 4 seconds? After 6 seconds? After 10 seconds? What will be its velocity at each of these instants?

11. A frictionless car starts down an inclined plane 10 times as long as the height of the raised end. What will be the acceleration of the car? What will be the velocity of the car after 5 seconds? How far will it travel in 5 seconds? In 4 seconds? In the fifth second?

12. A hill is 1000 ft long. What must be its height to give an automobile an acceleration of 4 ft/sec^2? What will its velocity be at the bottom? How long will it take the car to coast down the hill? (This acceleration is $\frac{1}{8}$ that of gravity.)

13. Describe an experiment by which the principles of accelerated motion may be determined.

14. What effect does gravity have upon bodies thrown upward? Thrown horizontally? Thrown downward? On bodies falling in a vacuum?

15. What is the momentum of a 5-ounce baseball thrown with a velocity of 100 ft/sec?

16. What is the momentum of a 1000-pound pile driver whose velocity is 30 ft/sec?

17. What is the momentum of a 3000-pound automobile moving at the rate of 30 mi/hr?

18. Make a clear statement of the Second Law of Motion. Give examples of its application.

19. A force of 15 poundals acts on a mass of 75 lbs that is free to move. What acceleration will be given to the mass?

20. A mass of 12 lbs is acted upon for 2 seconds and is given a velocity of 36 ft/sec. What acceleration is given the mass? What is the force in poundals? In pounds?

21. A 3-pound weight is hung on one end of a cord passing over a fixed pulley and a 5-pound weight is hung on the other end of the cord. What force moves the weights? What mass is moved? What acceleration will the system of weights have?

22. Which is harder to set in motion and by how much, a 1-pound mass or a 10-pound mass? Upon which is a greater gravitational force exerted and by how much? If free to fall, which will fall faster and by how much? Why?

23. A bullet is shot horizontally with a velocity of 2000 ft/sec. Neglecting air resistance, will the horizontal velocity of the bullet change before it strikes? When will the bullet begin to fall?

24. If the bullet in the previous question travels for 2 seconds before striking, how far will it have traveled horizontally? Vertically?

25. Compare the vertical motion of the rifle bullet shot horizontally with that of a bullet dropped at the same time. Is the Second Law involved? If so, how?

26. A stone thrown horizontally with a velocity of 80 ft/sec from the top of a cliff travels for 3 seconds before it strikes the earth. Is its horizontal velocity constant or variable? Is its vertical velocity constant or variable? How far will it travel horizontally? Vertically?

27. From the previous problem, indicate on a simple diagram the approximate position of the stone after 1 second, after 2 seconds, and after 3 seconds. What kind of line should connect these points and show the path of the stone?

28. A man pushes a heavy box with a force of 75 lbs. How hard does he push backward on the floor? Would rubber-soled shoes help him? Why?

29. A man in a large motor boat pulls a row boat up to him with a rope. Compare the momenta of the two boats. Compare their velocities. Which will move farther? Why?

30. A 125-pound gun fires a 1-pound projectile with a velocity of 2500 ft/sec. Compare the momenta and the velocities of the gun and of the projectile if the gun is unbraced. What is the velocity of the gun?

31. Why would it be unsafe to fire a 3-inch gun from an airplane? During the war a small cannon devised for airplanes shot an explosive shell in one direction and an equal mass of harmless fine shot in the other direction. What effect would firing such a gun have upon the stability of the airplane?

32. A boy jumps from the platform of a large spring balance. Will the balance indicate a number larger or smaller than his correct weight as he jumps? Why?

33. Two bodies of unequal mass are connected to each other by a stretched spring. If the two bodies are loosed at the same

time, how will the forces acting on them compare? Compare also the velocities, momenta, and accelerations of the bodies.

34. A 1000-pound ram of a pile driver is suspended above the earth's surface and then released. What force acts on the body and on the earth to bring them together? What acceleration will the ram have? What momentum after 1 second? Will the earth have an equal acceleration? An equal momentum? An equal velocity?

CHAPTER XXVII

HOW FORCES ACT TOGETHER

352. Translatory and Rotary Motion. — The forces applied to a stationary body tend either to move the body forward or to turn it around to a new position. A forward movement of the body is called *translatory* motion, while a motion of one part of the body about another part is called *rotary* motion. Both motions are frequently combined, as in a stick thrown "end over end," or in a moving automobile wheel. A body is in equilibrium when the forces tending to produce *both* translatory and rotary motion are balanced.

353. Combined Effect of Forces at a Point. — Often there are several forces acting on a body at a single point. These forces may act in the same direction, as in the case of several parcels being weighed on the same scales. Or, the forces may act in opposite directions, as in the case of a "tug-of-war." The combined effect of forces acting in a straight line will be the equivalent of their algebraic sum, denoting forces in one direction by a + sign and those in the opposite direction as −. Thus, a force of 15 lbs and one of 10 lbs in the same direction produce the same effect as one of 25 lbs. We see other practical illustrations of this in the pulling of a train by two locomotives, in the greater speed of a river steamer going downstream, and in the use of a second team of horses to pull heavy loads up a steep grade.

It may be easily inferred that if the forces act in the same line, but in opposite directions, the resultant of two equal forces would be zero. If the forces are unequal, their resultant is the *difference* of the forces and acts in the direction of the greater force. A floating body illustrates the equality of the downward force of gravity and the upward pressure of the water. When an object sinks in water, the effective (resultant) downward force upon it is the difference between its weight and the upward water pressure.

The preceding paragraph indicates that two or more forces acting in the same direction do not lose any of their effectiveness by acting together. This effectiveness decreases, however, as the angle between the forces increases, until it reaches a minimum, when the forces act exactly opposite each other. The slanting fall of wind-driven raindrops illustrates the combined effect of angular forces, one of which is vertical and the other horizontal. During rainstorms, when the wind does not blow, the drops trace on moving car windows the oblique resultant of the vertical fall and the horizontal motion of the car. A swimmer or a boat crossing in a strong current follows a course which is a resultant of the forward motion and the sidewise motion. A brook shows by its irregular course the effect of the combined forces of gravity and of obstructions in its course (Figure 515). These examples lead to the inference that the resultant of two forces at an angle takes a direction somewhere between the two forces, and that the amount of this resultant force depends upon the angle at which the forces act.

354. Experiments Illustrating Composition of Forces and Motions. — An experiment will show the general result of combining two angular forces, although the direction of the resultant and not its magnitude is shown.

Experiment 133. — Lay off squares an inch on a side on a small board. Make holes in the board at the corners of the squares so that nails may be set up in them. Lay a sheet of paper on the board and cover it with a sheet of carbon transfer paper. Set up two nails in any two holes in the board, hook a wide rubber band on the nails. Draw back the band and shoot a heavy steel ball across the carbon paper. *What are the forces acting to move the ball? In what directions do they act? How does the direction taken by the ball compare with the directions of these forces?* Vary the position of the nails and the length of the ends of the rubber band. *Can you find any relation between the direction of the ball and that of the two forces which propel it?*

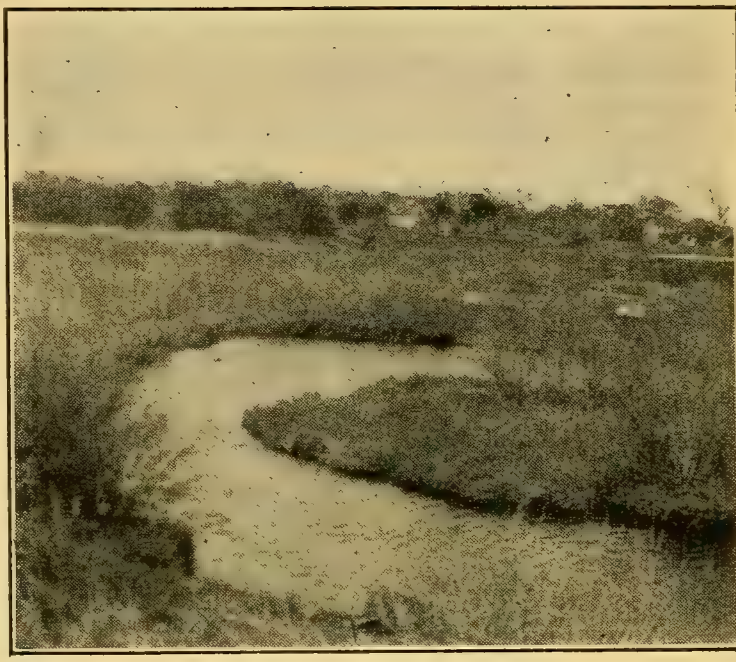

Figure 515. — Two angular forces, gravity and obstructions in its course, cause the stream to follow a crooked path.

If the resultant of two motions is to be determined, another simple experiment can be used which again shows only the general principle involved.

Experiment 134. — Place a sheet of paper on the corner of the table and stand a pencil point down on the side away from you. Have some one draw the paper to the right or left while you draw the pencil directly toward yourself. *What direction is taken by the pencil mark on the paper? Why?* This experiment may be varied by changing the speed of either paper or pencil, or the direction of either.

Another experiment may now be performed to make clear the exact method by which the combined effect of two angular forces may be determined.

Experiment 135. — Connect two spring balances by a cord and suspend them against the blackboard so that they may pull at an angle

with each other against a screen-door spring (Figure 516). Record the pull of the balances and draw chalk lines on the board under the cords to show the direction of their pulls. Remove the apparatus while you extend the force lines so that their length shall be proportional to the forces, according to some scale of measurement. Then complete a parallelogram on the two forces as sides, and draw the diagonal to the point of application of the forces. *What is the value of the force represented by the diagonal of the parallelogram according to the scale chosen?*

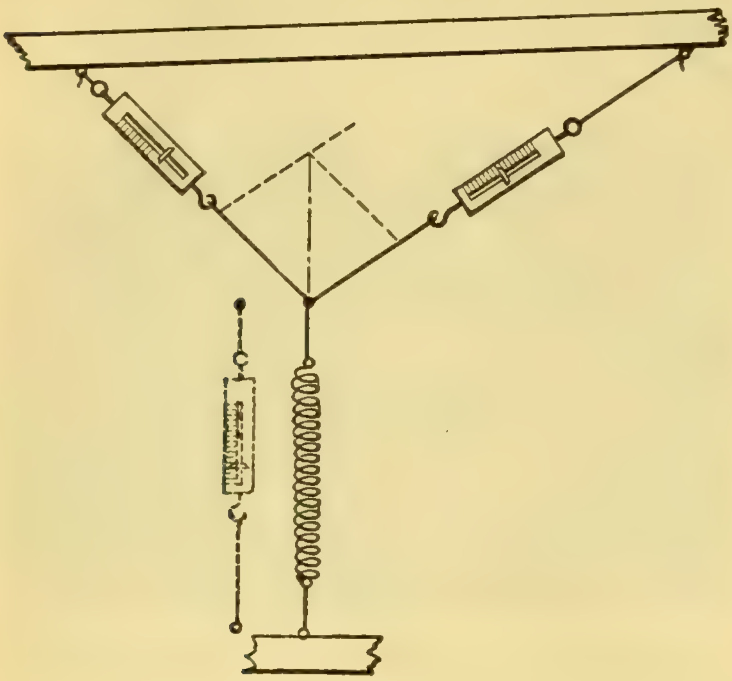

FIGURE 516.

Now replace the spring with a third spring balance and draw the cord to its previous position, marking the direction of the force of the third balance. *What is the value of the third force which opposes the two original balances? What is its direction as compared to the diagonal of the parallelogram? Would a single force represented by the diagonal produce equilibrium with the spring or the balance which replaces it? Is the force represented by the diagonal the resultant of the two angular forces?*

355. Steps in Finding the Resultant of Angular Forces. — A force may be represented by a line whose direction indicates the direction of the force, and whose length is proportioned to the amount of the force. Such a line is called a *vector*. 1. Draw a vector to some convenient scale to represent one of the given forces. 2. From the same point of application draw a vector to represent the other force, using the same scale. 3. On these two vectors as sides, construct a parallelogram. 4. From the point of application, draw a diagonal of the parallelogram. 5. Find the value of the resultant vector (diagonal) by applying the scale used in drawing the

vectors above. This diagonal vector shows the direction of a single force that will produce the same effect as the two given forces, and its magnitude as determined by the scale shows the value of the resultant of the two angular forces.

356. A Typical Solution. — Suppose we wish to find the resultant of two forces, one of 15 pounds acting east and one of 10 pounds acting 30° east of north. Choosing a scale of 1 inch = 5 pounds, we draw a line, *AB,* 3 inches long to the right of a given point of application. This line represents the 15-pound force acting east. A line, *AC,* 2 inches long is drawn from the same point of application 30° to the right of the vertical to represent the 10-pound force. On these two lines a parallelogram, *ABDC,* is constructed (Figure 517) and the diagonal vector, *AD,* is drawn. This line shows the *direction* of the resultant (east of northeast). Measuring this line, we find it to be 4$\frac{3}{8}$ inches long and this number multiplied by the scale number gives the *magnitude* of the resultant: 5 lb/in × 4$\frac{3}{8}$ in = 21$\frac{7}{8}$ lb force, the approximate value of a single force that will produce the same effect as the two given forces. This method is only as accurate as the work done in constructing the figure, but it is the only simple method of determining the resultant of angular forces except in the case where the forces are at right angles to each other.

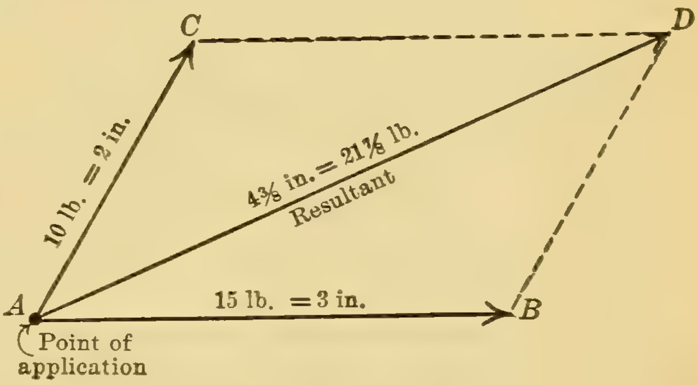

Figure 517.

If the two forces are at right angles, the figure must be drawn to ascertain the direction of the resultant, but the mag-

nitude is found by taking the square root of the sum of the squares of the sides of the force diagram. In the problem given above, the two given forces may be held in equilibrium by a single force of $21\frac{7}{8}$ pounds acting opposite to the resultant. This force is known as an *equilibrant*.

Any number of forces may be thus composed by using the resultant of any two of them to form a parallelogram with the third force. The resultant of the three forces may be used with the fourth and so on.

This method of determining resultants is called the *composition of forces,* and the resultant thus determined is known as the *vector sum*. Angular forces are in equilibrium when their vector sum is 0. This condition of equilibrium results when one of the forces acts in the direction opposite to the resultant of the other forces and is equal to this resultant.

357. Resolution of Forces. — A boy pulling a sled does not use all of his effort to move the sled forward. A part of the pull is directed upward, as can be seen when the sled rises over an obstruction in its path. A slanting guy wire attached to the top of a telegraph pole not only holds the pole erect, but tries to pull it deeper into the earth. We can push heavy objects along the floor more easily if they are low down, because the push against them is more effective than it would be if they were higher. These illustrations indicate that the whole effect of a force is not always exerted in the direction of the desired result. The method of finding out how much of a given force acts in a desired direction is called the *resolution of forces*. Any given force may be resolved into components acting in any given direction. In general, however, we content ourselves with determining the component that acts in the desired direction and the component at right angles to this valuable one.

Experiment 136. — Attach a 1000-gram weight to a vertical support, inserting a spring balance near the top of the cord (Figure 518). A light wooden boom beveled to fit a notch in the support is used to hold the cord away from the vertical support. The apparatus now represents somewhat the conditions in a boom derrick. Drive a small nail into the end of the boom and wind one turn of the cord around the nail. Attach a second spring balance to the cord just above the nail and pull horizontally outward until the boom falls from the notch in the post. The reading of the upper balance shows at this time the effect of the 1000-gram force exerted along the cord, and the other balance shows the effect of this weight in compressing the boom horizontally. In other words, the 1000-gram force has been resolved into two components, one acting obliquely downward on the post and the other acting horizontally along the boom. The reaction to these two components is a force acting obliquely along the cord and one acting horizontally outward along the boom. If the direction of the three forces is carefully marked on a paper held against the cords, the force diagram may then be completed by measuring off the reaction forces and the weight according to some convenient scale. The diagonal of a parallelogram constructed on the boom and cord vectors will be found to represent a resultant that is exactly equal and opposite to the downward pull of the 1000-gram weight.

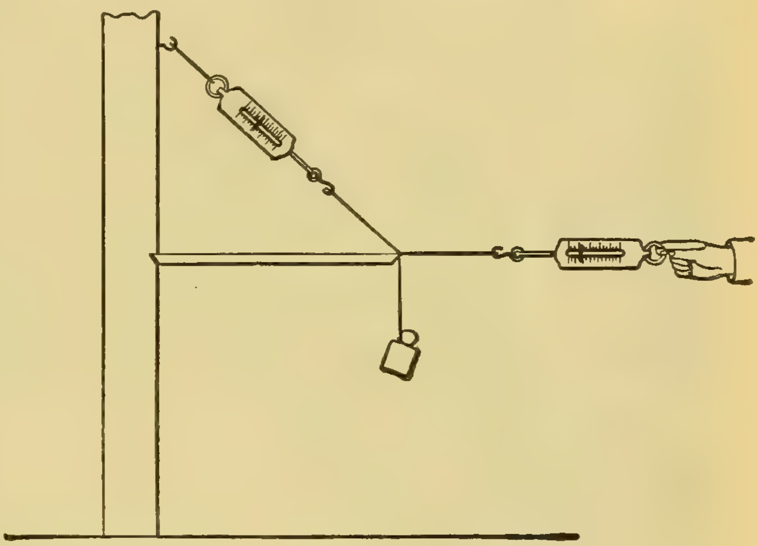

Figure 518.

In Figure 519, the forces in a derrick are shown in their usual relation to each other. The downward pull of the load of rock is overcome by an equal upward pull. This upward pull is in turn resolved into two components, the *pull* of the ropes upward to the right, and the *push* of the boom upward to the left. Thus the weight of the rock is seen to exert forces other than downward ones.

358. Resolution of Force of Gravity on an Inclined Plane. — When a weight rests on a *horizontal* plank the whole gravitational force acting on the weight tends to break the plank, but there is no horizontal component of gravity tending to move the weight along the plank. As one end of the plank is

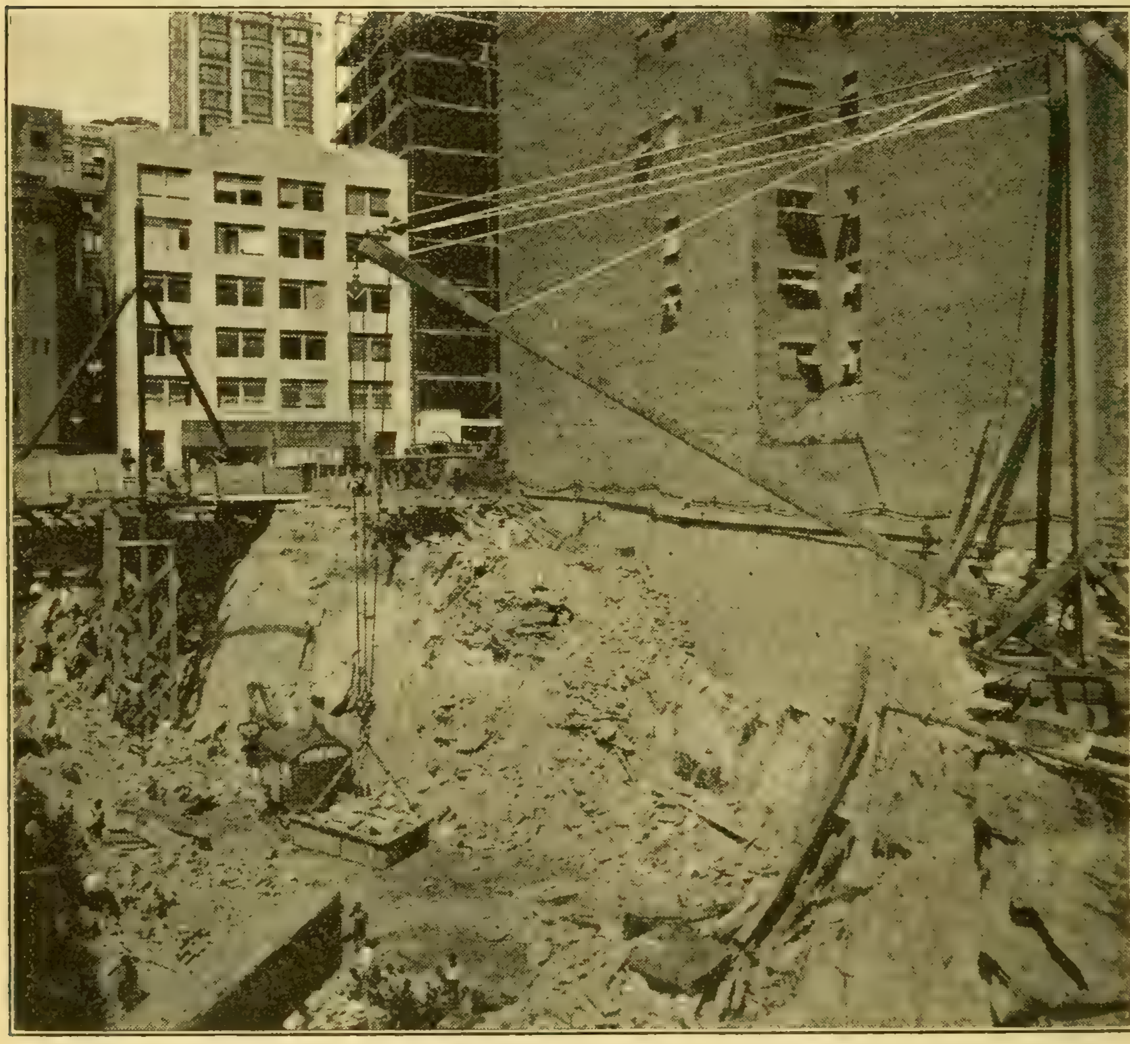

FIGURE 519. — A DERRICK IN ACTION.

lifted, however, a component of gravity begins to make the weight slide down the plank, unless force is used to prevent this. At the same time, the perpendicular component acting against the plane becomes less. As the slant of the plane becomes greater, the component parallel to the plane becomes greater, making necessary a greater force to hold the

weight from sliding down the plane. The perpendicular component becomes less until, when the plane stands vertically, the whole gravitational force acts parallel to the plane and no component of it tends to break the plane. In the force diagram (Figure 520), the relation between the gravitational force and its component parallel to the plane is seen to be the same as the ratio of length of the plane to its vertical height. This is in accordance with § 357. The exact value of these two components of the force of gravity acting on the body on the inclined plane may be found by experiment.

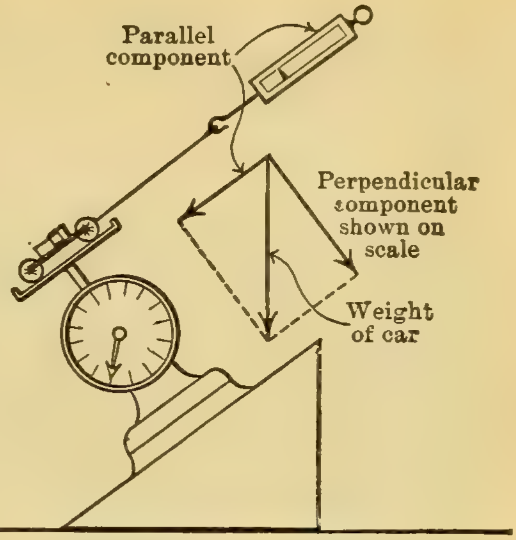

FIGURE 520. — Force diagram to show how the weight of the car on the plane is resolved into two components.

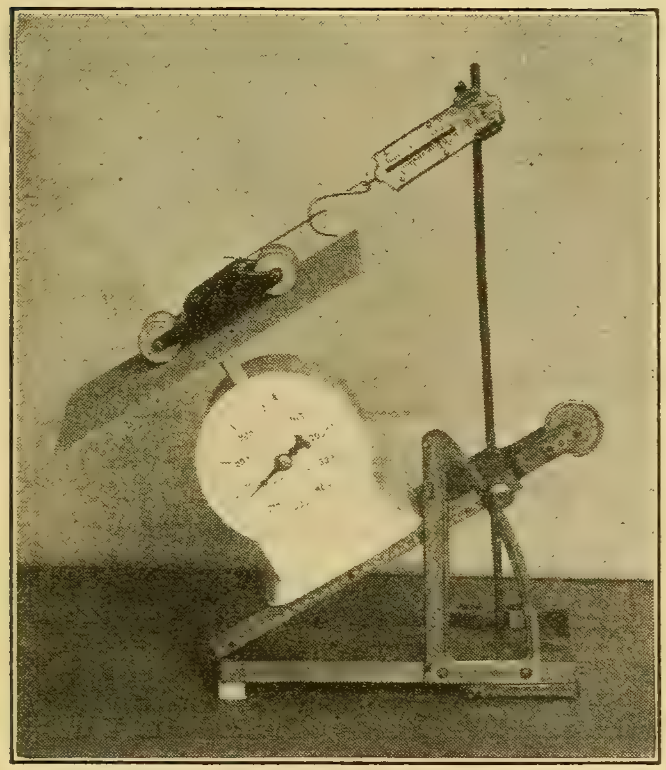

FIGURE 521. — FORCES ON AN INCLINED PLANE.
What does each scale measure?

EXPERIMENT 137. — Place a stiff cardboard on a household scale or a diet scale, keeping the board from sliding by means of thumb tacks in it. On the cardboard place a "frictionless" car, and keep it in position by a cord attached to a spring balance (Figure 521). Tip the scale by tilting the plane and read both balances. The downward pull of gravity is resolved into two components — one perpendicular to the plane and measured by the diet scale, the other parallel

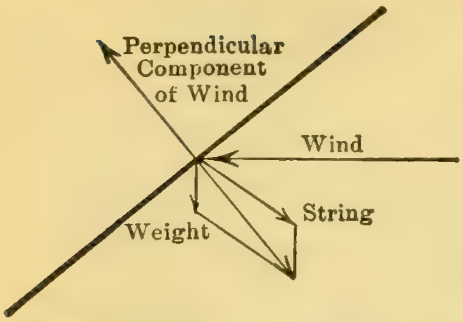

FIGURE 522. — Force diagram to show the relation of the three forces acting upon a kite.

to the plane and measured by the spring balance.

The experiment may be varied by changing the slant of the plane. *How do the components change as the plane becomes steeper? When will the perpendicular component become greatest? When zero? When will the parallel component become greatest? When zero?*

359. Applications of Resolution. — In addition to the illustrations already given, there are many other cases of the resolution of a force into two or more components. A flying kite (Figure 522) is acted upon by three angular forces — gravity, the pull along the string, and the wind. The wind, acting horizontally against the oblique surface of the kite, does not act in a direction opposite to the resultant of the other two forces. The force of the wind may, however, be resolved or considered as two components, one slipping along the kite parallel to the kite, the other acting perpendicularly against the kite. The perpendicular component is equal and opposite to the resultant of the pull of gravity and of the string. The kite remains in equilibrium under these conditions because the vector sum of all the forces is equal to zero. Variations in the pressure of the wind bring about constant readjustments of the position of the kite.

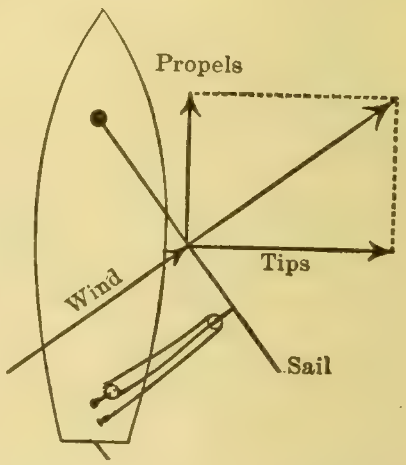

FIGURE 523. — A sailboat running in any direction except directly with the wind makes use of only a part of the force of the wind. The other component tips the boat.

When a sailboat travels directly with the wind, the whole force of the wind against the sail is utilized in moving the

boat forward. In sailing at an angle with the direction of the wind, the sail is held obliquely to the wind (Figure 523). The force of the wind may then be resolved into a useless component parallel to the sail, and an effective component at right angles to the sail. But the sail itself is set obliquely to the desired motion of the boat, so that the perpendicular component of the force of the wind against the sail must be also resolved into two components — one acting along the direction of the motion of the boat, the other tending to cause the boat to tip and drift sidewise (Figure 524). The drifting component is neutralized to a considerable extent by the use of a keel or a centerboard.

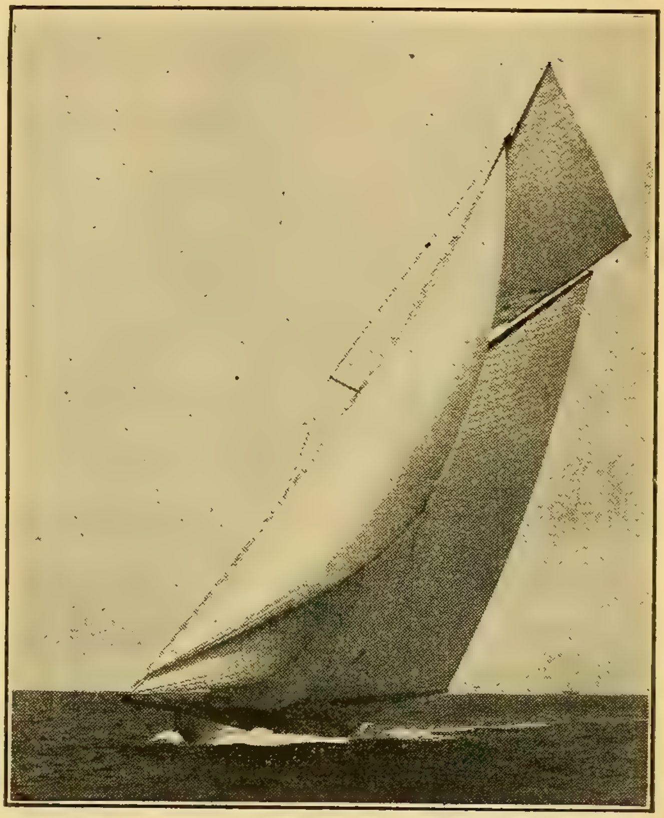

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FIGURE 524. — UNDER FULL SAIL.

The shape taken by the sails shows a forward component of the force of the wind.

A picture hung by slanting cords causes the cords to exert a reaction to the weight of the picture. This reaction along the cord may be resolved into an upward component, which supports the weight of the picture, and a horizontal component, which tends to pull the fastenings of the cord in toward each other. The greater the angle between the cords,

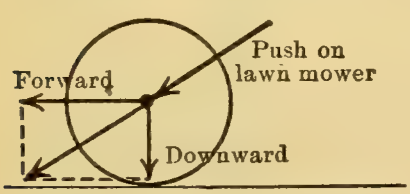

FIGURE 525. — FORCES EXERTED ON A LAWN MOWER.

the greater the amount of this useless horizontal component, and the greater must be the strength of the cord to support a given picture. Not all of a man's push on a lawn mower is effective in moving the mower forward (Figure 525). His oblique push along the mower handle moves the mower forward and also pushes it into the ground. Where the grass is hard to cut he lowers the handle of the mower in order to increase the value of the horizontal, forward component.

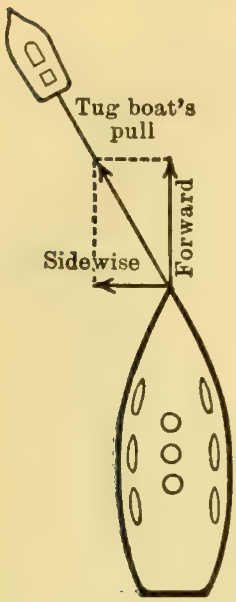

FIGURE 526. — Force diagram to show the effectiveness of the tug's pull on a larger boat. Which component is the valuable one?

Other illustrations of the principle of resolution are shown in Figures 526, 527, and 528. Figure 526 shows the oblique pull of a tug-boat resolved into a valuable forward component and a useless sidewise one; 527 shows that the oblique thrust of a roof consists of an outward and a downward component. In Figure 528, we observe that the slanting guy wire pulls the pole both sidewise and downward since the single force along the wire is resolved into components in these directions.

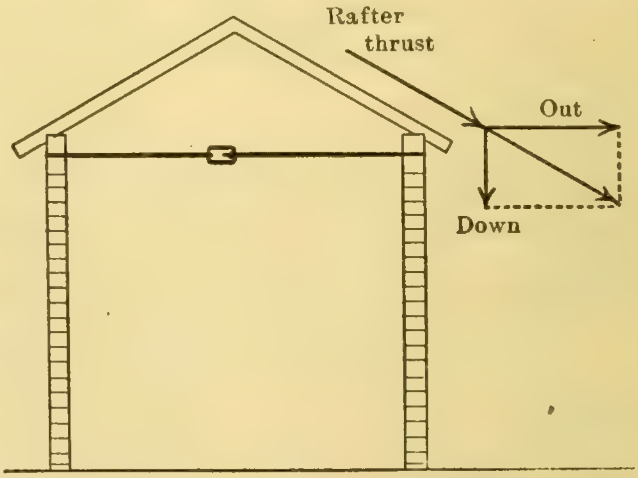

FIGURE 527. — The weight of the roof pushes the wall downward and outward. What balances these two components?

It may be of value to repeat that all forces may be resolved into as many different pairs of components as desired. Considered from the

point of view of the force diagram, the given force is always the diagonal of a rectangle whose sides are the required components. It is plain that on a given diagonal, any number of rectangles can be constructed, and the sides of these figures would constitute a pair of components into which the given force may be resolved. As stated, we generally consider only the component that acts in a desired direction and the one at right angles to this desired one.

Motions, like forces, may be resolved into component motions, in the same way as forces are resolved. For example, the oblique flight of a projectile may be resolved into a vertical and a horizontal component.

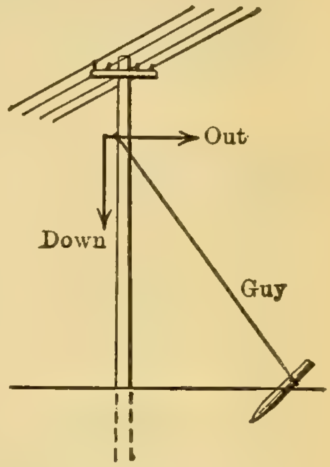

FIGURE 528.—A guy wire is put on a telegraph pole to prevent it from tipping over. Pick out the useful component and consider the effect of fastening the guy wire farther from the base of the pole.

QUESTIONS

1. Distinguish between translatory and rotary motion. Give two examples of each.

2. What kind of motion does an automobile wheel have? Give another example of the same kind of motion.

3. Give examples of the effect of forces acting at an angle with each other.

4. How does the value of the resultant of two forces at an angle compare with their sum? With their difference?

5. What is a vector? What things about a force may be shown by a vector?

6. Make a force diagram of a vertical force of 60 lbs acting at the same point as a horizontal force of 80 lbs. What is the magnitude of the resultant?

7. In Figure 529, *OA* and *OB* are vectors representing forces of 16 and of 24 lbs respectively, acting at an angle of 60°. Complete the

force diagram and determine the approximate resultant of the two forces.

8. In Figure 530, OA represents the force with which a man rows a boat directly across stream. OB represents the force of the stream at

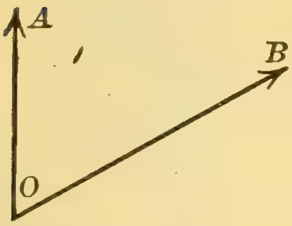

FIGURE 529.

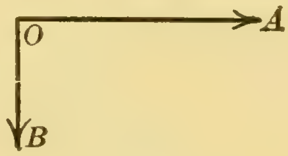

FIGURE 530.

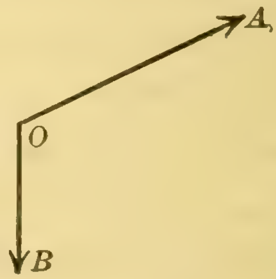

FIGURE 531.

right angles to the boatman's effort. If OA and OB are great enough to give the boat a velocity of 4 mi/hr and of 2 mi/hr respectively, find the approximate velocity of the boat and show the direction of its motion.

9. In Figure 531, OA and OB represent velocities of 4 mi/hr and of 2 mi/hr respectively. OA shows the direction of a man's effort in rowing a boat diagonally upward across stream, while OB shows the direction of the current of the stream. Show the resultant direc-

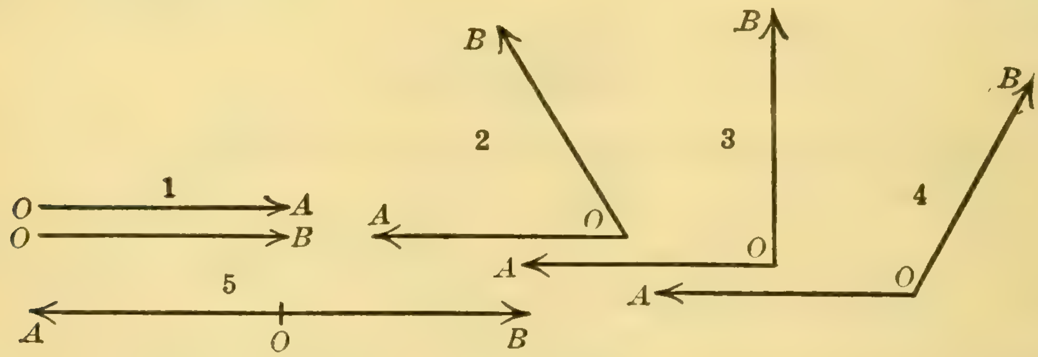

FIGURE 532.

tion of the boat and find the approximate velocity of the boat in this direction.

10. In Figure 532, OA and OB represent forces of 50 lbs each. Determine the resultant of the two forces at the angles indicated: 0°; 60°; 90°; 120°; 180°.

11. A picture is hung in the usual fashion by running a cord from one side of the picture obliquely up over a nail and then to the other side of the picture. If the tension in each cord is 7 lbs, and if the parts of the cord are at an angle of 90°, what downward pull is exerted on the nail?

12. What part of a force diagram represents the resultant of forces acting at an angle? If a body is acted upon by two forces simultaneously, one capable of giving it a velocity of 24 ft/sec south, the other capable of giving it a velocity of 32 ft/sec east, how far south and how far east will the body be after 1 sec? Show by diagram.

13. A body is given a velocity of 40 ft/sec in a direction a little east of southeast. Determine its eastward and its southward velocity. (See previous problem.)

14. What part of a force diagram represents a given force whose components are to be determined? What parts of the diagram represent the two components?

15. A northeast force of 100 lbs has an east component of 71 lbs. What is the north component of the 100-pound force?

16. One side of an oblique picture cord, making an angle of 45° with the vertical, pulls with a force of 7 lbs on its fastening. How much weight can this cord support? What force is exerted horizontally by the cord?

17. A guy wire acts at an angle of 30° with a telegraph pole. Show the direction of the component of the pull along the wire which is effective in holding the pole upright. What effect has the vertical component?

18. A sail is set at an angle of 60° to the wind. Show the valuable and the useless components of the force of the wind against the sail.

19. A man pushes a lawn mower whose handle is at a 45° angle with the ground. Show by diagram the valuable and the useless components of the force exerted by the man.

20. In the previous question, what change in the position of the handle would the man make if the mower becomes more difficult to move? What effect would this have upon the horizontal component?

21. What does the weight of a slanting roof tend to do to a vertical side wall supporting it? In what direction does the weight of a dome push on the vertical wall supporting it? Illustrate each answer by a diagram.

22. A boy draws a sled with a rope, which makes an angle of 30° with the horizontal. Show the component that moves the sled forward. Is the vertical component valuable?

23. A camp hammock is swung between two trees. Resolve the oblique force along the hammock cord into a component which supports

the weight in the hammock and a component at right angles to this valuable component.

24. With the same person in the hammock, would it make any difference in the tension in the cord if the hammock is swung more nearly straight?

25. If the trees to which the hammock is attached are slightly flexible, how will they bend when a person sits in the hammock? Why?

26. Show by diagram how the force of gravity acting on a weight on an inclined plane may be resolved into two components, one parallel to the plane and one perpendicular to it.

27. In the previous question, how would the parallel component change as the plane becomes steeper? How would the force required to keep the weight from sliding down the plane change?

28. If a barrel of sugar is to be rolled up an inclined plane, how does the perpendicular component of the weight change as the plane becomes steeper? How does the necessary strength of the plane change as the plane becomes steeper?

29. Show how the weight of a slanting house roof pushes on the vertical walls of the house. Suggest a method of overcoming the outward component. Does the outward component change if the roof is made steeper? If the roof is of tile instead of shingle?

360. Parallel Forces. — When two horses pull a wagon, the forces act in parallel directions. The same thing occurs when two or more men lift a heavy timber or rail. In determining the combined effect of the parallel forces it is necessary to know the magnitude and direction of the forces, and also the tendency of one to rotate the body around the other. If the two horses mentioned above were of equal strength, the whiffletree on which they pull would be fastened to the wagon at its center point. Should the horses be unequal in strength, or if three horses were used, the whiffletree would be so attached as to give the weaker side the longer portion of its length. A similar arrangement is used in the children's seesaw, where the heavier child must take the shorter end of

the plank. The principles underlying the proper arrangement of parallel forces can be learned from an experiment.

EXPERIMENT 138. — Attach cords and spring scales to a meter stick, as shown in Figure 533. Draw the cords tightly enough to cause scale C to read nearly its maximum. Adjust the cords until all are parallel and the meter stick is parallel to the table edge and perpendicular to the cords. Read the scales and observe the distances AC, BC, and AB. Since C obviously balances A and B, it may be considered as the equilibrant and to be equal and opposite to the resultant of A and B. Calculation will now show that $A + B = C$. This means that the resultant of two or more parallel forces is equal in magnitude to the sum of the forces. It can also be shown that $A \times AC = B \times BC$. This means that the resultant of the two parallel forces will be applied nearer the larger force than the smaller.

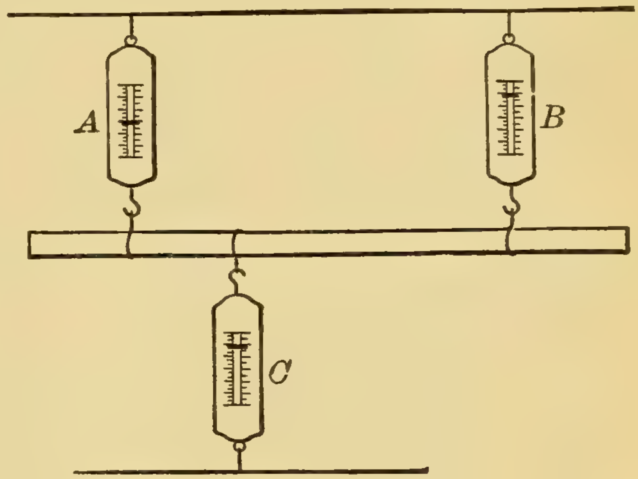

FIGURE 533.

EXPERIMENT 139. — An interesting variation of the preceding experiment is possible if a pair of so-called "diet" scales are available. These scales have a loose dial, which may be moved so as to have the needle indicate zero, even if there is a weight on the platform. Set the

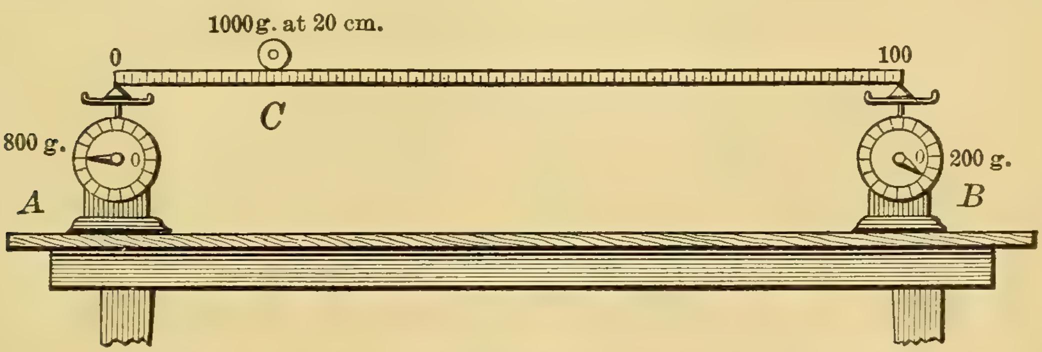

FIGURE 534.

two scales one meter apart, place a meter stick from one platform to the other, and reset the dials so that the pointers indicate zero. This eliminates the weight of the stick from the calculations which follow. Now place a weight on the stick first at the middle, then at unequal dis-

tances from the ends (Figure 534). In each case, how does the sum of the scale readings compare with the weight on the stick? How does the product of $A \times AC$ compare with the product $B \times BC$? How does the product $A \times AB$ compare with product $C \times CB$?

361. Moments. — In the preceding experiment, where three parallel forces acting on a body are in equilibrium, we have seen that translatory motion was impossible because the sum of the forces in one direction equaled the force in the opposite direction. If the stick is stationary, this will be true no matter how many parallel forces act on the bar. But it is also shown that the effectiveness of a force in rotating the stick depends upon the position of the force, as well as upon the amount of the force. The second condition of equilibrium of parallel forces is that the turning effects of the several forces must also be balanced. *The turning effect of a force is called the moment of the force; the moment of force is measured by the product of force × force arm,* the force arm being the perpendicular distance from the line of the force to the center of rotation (Figures 533 and 534). According to the law of moments, when a body is in equilibrium, the sum of the moments of force tending to rotate the body in a clockwise direction must equal the sum of the moments tending to rotate the body in a counterclockwise direction. Referring again to the preceding experiment (138), it is seen that if C is taken as a center of rotation, or *fulcrum,* the moment of A about C (clockwise) equals the moment of B about C (counterclockwise). Any point on the stick may be considered as a fulcrum and the law still holds good; or any number of forces may act on the body without causing a departure from this principle.

362. Applications of the Principle of Moments. — When a man picks up one end of a heavy log or timber, the moment

of his force is counterbalanced by the sum of the moments of all the gravitational forces acting on the timber. The end of the timber resting on the ground is the center of rotation of fulcrum for both the man's force and gravity's pull. But while all of the man's effort is exerted through a force arm which is the whole length of the timber, the gravitational forces acting on the particles of wood near the fulcrum have only a short force arm. Of course those particles of wood near the man have a longer force arm than the ones near the fulcrum, but all taken together the *average* force arm through which gravity acts is only *one half* the length of the timber, provided the timber is uniform in section. Its weight may then be considered as being concentrated at the center of the timber, this point being known as the *center of gravity* of the body. If the man lifts one end of the timber, his force arm is twice as long as that of gravity, hence he exerts a force that is only one half the weight of the timber. If the timber is bigger at one end, the center of gravity is nearer the heavy end. To move the timber out of the way, the man will now lift the small end. This makes the force arm of the weight small; the moment of gravity's force is small and the effort required of the man to overcome this moment is small.

363. Levers. — The lever has been in use for centuries; probably at first it was used to dig up edible roots or to pry rocks out of the ground or to move logs out of the way. It has since been developed into oars, paddles, shovels, and a wonderful variety of other tools and appliances. In most cases the lever is used either to do work with less effort or with greater speed.

Theoretically, the lever is a weightless bar upon which an effort may be applied to overcome a resistance. The bar is

pivoted at some point around which it moves as the result of rotary forces. Levers are for convenience divided into three classes, in which the fulcrum, the resistance, and the effort are respectively placed between the other two elements (Figure 535). The principle of moments applies equally to any form since, when only two forces are applied outside the fulcrum, the moment of the effort used (effort × effort arm) = the moment of resistance overcome (resistance × resistance arm). On a seesaw children of equal weight sit at equal distances from the fulcrum, but a heavy child sits nearer the fulcrum (Figure 536), so that the moments of each may be equal. A crowbar raises heavy stones when a small effort is applied because its resistance arm is small compared to its effort arm. A heavy load can be lifted in a wheelbarrow for the same reason. On the other hand, less weight can be lifted in a shovel than directly, because the hand at the center of the handle (effort) has a shorter force arm than the coal or snow (resistance).

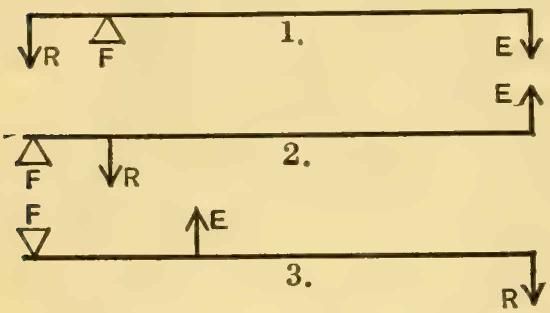

FIGURE 535. — THE CLASSES OF LEVERS.

First, fulcrum between *R* and *E*. Second, resistance between *F* and *E*. Third, effort between *F* and *R*.

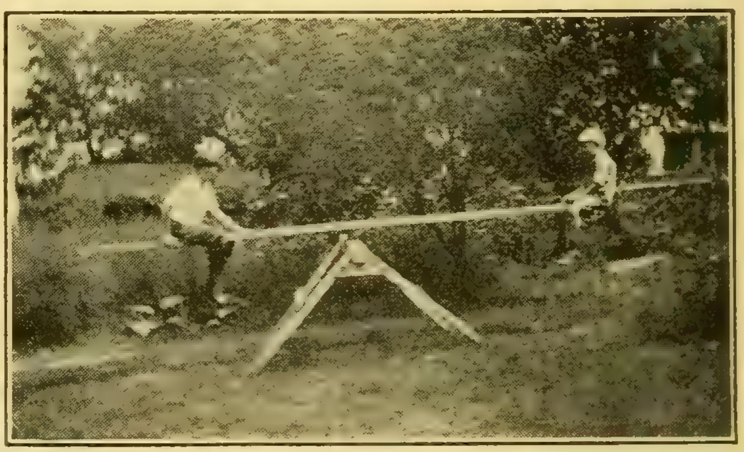

FIGURE 536. — SEESAW.

When the larger boy sits nearer the fulcrum, the moments are equal and a slight force moves the plank.

Shears, sugar tongs, nutcrackers, pump-handles, pliers, and the various movable bones of the body are included in the types of levers.

364. Moment Solution of Lever Problems. — The first step in the solution of lever problems should be the construction of a simple diagram showing the magnitude of the forces, their points of application, their direction, and the distances of the forces to the fulcrum. Suppose it is required to find how great an effort is needed to lift a 500-pound weight attached to one end of a 12-foot bar at a distance of 2 feet from the fulcrum. Figure 537 shows the positions and distances. The moment of the resistance is $500 \times 2 = 1000$, counterclockwise. The effort moment is $10 \times E = 10\,E$, clockwise. Since, by the principle of moments, $10\,E = 1000$, then $E = 100$ pounds, the effort required.

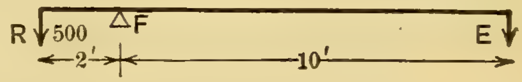

FIGURE 537. — EQUILIBRIUM IN A LEVER OF THE FIRST CLASS.

If the weight of the bar is included in the problem, the only additional step is to consider the weight as a single downward force acting at the center of gravity. A 12-foot pole weighs 90 lbs and has its center of gravity 5 ft from one end, which rests on the ground. A 525-pound weight is placed 2 ft from the end on the ground. How great an effort at the small end of the pole is required to raise the weight? A diagram (Figure 538) shows positions, directions, and dis-

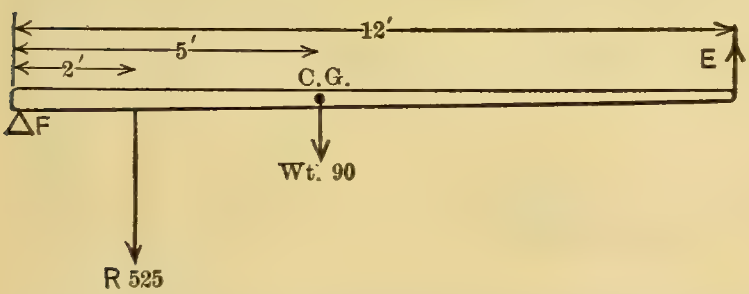

FIGURE 538. — The weight of the lever is considered to act as a single force at the center of gravity of the lever.

tances. The weight of the pole acting at the center of gravity is 5 ft from the fulcrum, hence a clockwise moment of $5 \times 90 = 450$ is produced. The 525-pound weight at 2 ft from the fulcrum produces a moment of $2 \times 525 = 1050$, also clockwise. The unknown effort E at 12 ft from the fulcrum produces a moment of $12\ E$, counterclockwise. Since clockwise moments must equal counterclockwise moments:

$$12\ E = 450 + 1050.$$

$$E = \frac{1500}{12} = 125 \text{ lbs, the effort required.}$$

The moments of any number of forces may be thus calculated and any unknown force or distance may be determined. If a weight is placed on a beam or bridge supported at the two ends, one support may be considered as the fulcrum and the other as the effort (Figure 539). Having found one force, the other may be found by subtracting the first force from the weight, since the sum of the upward forces equals the downward force (§ 360).

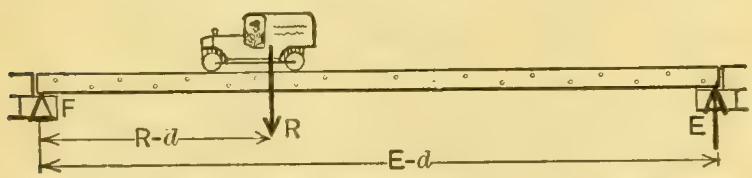

FIGURE 539.—To find how the weight upon a bridge is distributed, consider one support of the bridge as a fulcrum and the other as an effort pushing up that end of the bridge.

QUESTIONS

1. Where would you put the support for a seesaw when there is one child at each end, assuming that they have equal weights? When there are two on one end and one on the other? When there are two on one end and three on the other?

2. A laborer uses a crowbar as a lever whose effort arm is 5 ft and whose resistance arm is 1 ft. How many pounds force must he use for each 5 lbs of resistance to be overcome? How much resistance can be overcome with 40 lbs effort?

3. The handles of a wheelbarrow are 3 times as long as the distance from the center of the load to the axle. What is the mechanical advantage gained by the use of the barrow as a lever? What force at the handles will lift 150 lbs in the barrow?

4. A 200-pound weight is placed on a 15-foot beam supported at the ends. If the weight is 6 ft from one end, how much of it is supported by the nearer end? By the farther end?

5. A simple platform scale has a weight arm of 1 in, and its sliding counterpoise weighs 2 lbs. At what distance must the counterpoise be placed when the weight on the platform is 20 lbs? What weight is on the platform when the counterpoise is at 12 in?

6. Give examples of common devices which depend upon the lever principle for their usefulness. In each case, show how the lever involved does the required work.

7. A man uses a 12-foot uniform timber weighing 50 lbs as a lever of the second class to lift a weight of 300 lbs placed 2 ft from the end on the ground. If the center of gravity is at the center of length, what moment will the weight of the timber produce about the stationary end? What moment will the load produce about the stationary end? What moment must the man produce to raise the weight? What effort must he use?

365. Universal Gravitation. — The fall of bodies to the earth convinced Newton of the existence of an attraction between objects and the earth. This attraction we have called *gravity* and the measure of it is known as the *weight* of the object. According to the third law, this attraction acts upon the earth as much as upon the object. No noticeable effect is produced upon the earth, however, because of its great mass.

Newton concluded from the action of objects with the earth that a similar attraction must exist between all bodies in the universe. *This gravitational attraction varies directly as the product of the masses of the two bodies and inversely as the square of the distance between them* (Newton's Law of Universal Gravitation).

Between small objects, such as surround us, this gravitational effect is too small to be noticeable. When the bodies are of the size of the members of our planetary system, the attraction between them produces effects that are of great magnitude and of considerable importance. Thus the gravitational attraction between the earth and the moon causes the tides and also acts as a centripetal force to hold the moon in its orbit around the earth. The sun, although much larger than the moon, produces less effect upon the tides than the moon does, because the sun is so much farther away. The planet Neptune was located by its gravitational effect upon other planets before it was seen through the telescope. The Newtonian law of gravitation furnished an explanation of the modern conception of our solar system.

366. Pendulum. — We must revert to Galileo for the origin of our knowledge of the pendulum. A swinging chandelier gave him the idea that the swings of the pendulum are accomplished in equal intervals of time regardless of the size of the *arc* through which the body moves. Investigation showed that the weight of the bob and the number of degrees through which it swings (if not too great) have no effect upon the time required for one vibration.

Experiment 140. — Many of the facts concerning the pendulum are easily learned from experiments. A number of these experiments given here may be performed either at home or in the laboratory. A convenient support for a pendulum is made by nailing a thin cork to the cross bar of the laboratory table and cutting a vertical slit in the cork with a sharp knife. A light thread may then be drawn into the slit and the pendulum adjusted to any length (Figure 540).

To show the effect of weight or material upon the period of the pendulum, support in turn balls of wood, steel, and lead, being careful that the center of each ball is the same distance from the support. Count the swings of each for 20 seconds. *Does the material or weight of the pendulum affect its period?*

To show the effect of the size of the arc through which the pendulum swings, count any pendulum for 20 seconds as it swings through a small arc, and then for the same time as it swings through a larger arc. *What is the effect of the size of the arc upon the period of vibration?*

Adjust a pendulum so that its length is exactly 9 inches from support to the center of the ball. Count its swings for 20 seconds. Lengthen it first to 16, and then to 25 inches, counting its swings for the same interval of time. *Which makes more swings per second? Does the number of swings per second vary inversely as the length of the pendulum, or as the square root of its length? What relation exists between the length of the pendulum and the period of time required for one swing?*

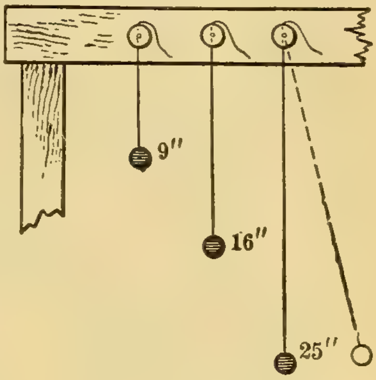

FIGURE 540.

367. Period of the Pendulum. — The period of vibration does depend upon the length of the pendulum, varying directly as the square root of the length. The period also varies inversely as the acceleration due to the gravity, since it is a component of gravity's downward pull that causes the body to swing when it is released after being moved sidewise.

The relation between time of vibration (**t**), length of the pendulum (**l**), and gravity's acceleration (**g**) is expressed by:

$$t = \pi\sqrt{\frac{l}{g}}.$$

Since **t** and **l** are measurable and π is a constant, the value of **g** (gravity's acceleration) may be determined for any place. We have seen that this value varies slightly with the latitude and the altitude of the place.

Pendulum clocks make use of the regularity of the swing of the pendulum. Each swing of the pendulum allows a spring, or weight, to move a wheel a certain distance. This movement is transmitted to the hands by means of gears.

The pendulum is kept in motion by a slight force applied as the pendulum passes its lowest point. Science has in this way provided an exact method of measuring time. This method replaced such clumsy and inaccurate devices as measured candles, hour-glasses, sundials, and the so-called water-clocks such as Galileo himself used in timing his experiments. Huyghens was the first to apply Galileo's discovery to practical use in clocks.

368. Stability. — A book lying on the table keeps its position without difficulty, but can be made to stand on end only with some trouble. In the same way a pencil lies on its side without any tendency to tip over; it can, with some care, be made to stand on its unsharpened end, but will not stand alone upon its sharp end. Boxes, chairs, stools, and all common objects differ in their tendency to retain a given position. This *stability* depends upon the shape, weight, and position of the object. Common knowledge shows us that heavy objects are harder to tip over than light ones, and that the broader the base of the object the more stable it is.

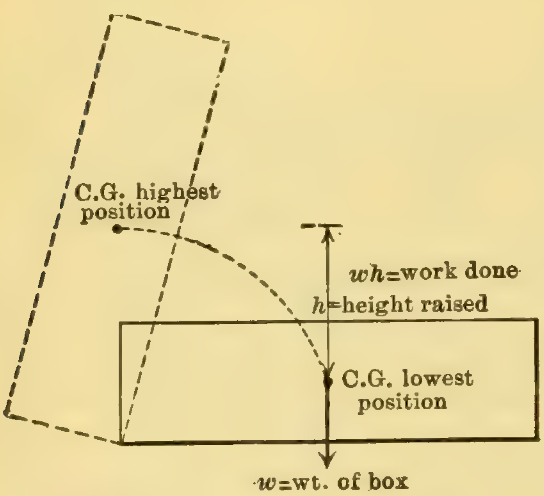

FIGURE 541. — The stability of a box is greatest when the most work has to be done to tip it to a new position.

The stability of an object is measured by the amount of work required to make it take a new position. In Figure 541, w indicates the weight of the box, and h the height to which the center of gravity must be raised before the weight of the box will make it take a new position. Then wh is the work done in tipping the box up on end. In the other figure (542)

it is seen that the product wh is much less because of the smaller value of h. In this case the less amount of work required to tip the box back upon its side is the measure of the smaller stability while on its end. The stability of an object is greatest when its center of gravity is at the lowest level. This fact is illustrated by the loading of cars, trucks, and ships, where heavy objects are placed at the bottom of the load. Sailboats are tipped by the force of the wind and are consequently ballasted with a lead keel or otherwise to keep the center of gravity low. The old-fashioned high bicycle owed some of its insecurity to the high center of gravity of its rider. The word *tumbler* as applied to drinking glasses comes from an early practice of weighting the bottoms of such vessels in order that they might be less easily upset.

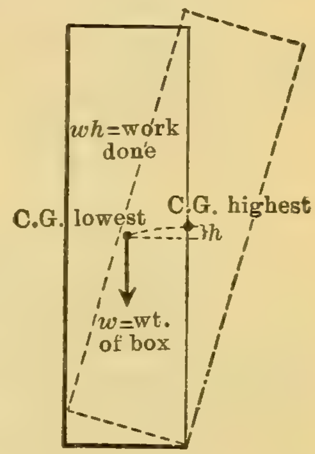

FIGURE 542. — In this position of least stability, the center of gravity of the box needs to be raised but little to cause the box to seek a new position.

369. Three States of Equilibrium. — Objects like the pencil mentioned above can be so placed that they will either (1) remain in that position and return to it if slightly tipped, or (2) take a new position like the first and remain in this position until disturbed, or (3) seek a different position. To these three conditions of equilibrium are given the names *stable, neutral,* and *unstable.* A cone standing on its base is in stable equilibrium because work must be done on it to tip it over to a different position. A line downward from the center of gravity falls within the broad base of the cone.

If the cone is laid on its side, its center of gravity is at a level that does not change as the cone is rolled along. A vertical line downward from the center of gravity passes

through the line of support. No work is required to move the cone against gravity in rolling the cone and the cone in this position is said to be in *neutral equilibrium.*

If the cone is stood on its vertex, it immediately falls to a different position. No work is required to bring about this change, but, on the contrary, the cone does work in tipping over. The cone supported by a force applied to a single point below the center of gravity of the cone is in *unstable equilibrium.*

QUESTIONS

1. State the Law of Gravitation. What is its importance to science?

2. Name two factors that affect the period of vibration of a pendulum. Name two factors that do not affect its period.

3. Why is a pendulum used in clock construction? If a clock gains time, what change should be made in the pendulum? Why?

4. Compare the stability of a brick on each of its three dissimilar faces. What factors determine the stability of the brick?

5. Compare the stability of a load of lumber with that of a load of stone. Of a book on its side with that of a book standing on its end. Give reasons.

6. A bowl can be held inverted on the finger, but cannot easily be held upright in the same way. Explain.

7. Name, define, and illustrate the three states of equilibrium.

370. Circular Motion. — We have all seen water fly off from a moving wheel. A common trick is to whirl a pail of water in a vertical circle without spilling the contents when the pail is upside down. We must infer that there is some force holding the water in the pail when gravity is trying to empty it. Since all actions or forces are accompanied by equal and opposite reactions or forces, it is possible to consider the force that holds the water in the pail as the reaction to a force that tends to make both pail and water move

toward the center instead of in a straight line. This inward force is exerted along the arm that whirls the pail. These two forces, acting equally in opposite directions, are called *centripetal* (acting toward the center) and *centrifugal* (acting away from the center). These forces act on every rotating mass with a stress depending upon the mass of the body in rotation and the speed and radius of rotation.

The centripetal force usually receives little consideration, because its visible effects are negative. We do not realize that there is a force keeping a whirling wheel from flying apart, because as long as the wheel holds together the force produces no visible, positive effects. The centripetal force acting on most rotating bodies simply holds the parts of the body together and can therefore be no greater than the strength of the material used in making the whirling device.

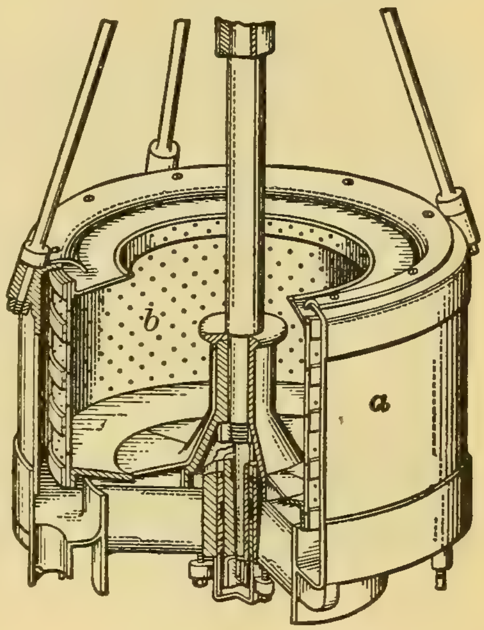

FIGURE 543. — CENTRIFUGAL FILTER.

Centrifugal force drives the water from wet material in (*b*) through holes into the outer casing (*a*).

371. Applications of Centrifugal Force. — The centrifugal force, which is the reaction to the centripetal force, does produce effects that can be easily observed. It pulls the water off the moving wheel, causes automobiles to skid as they turn corners too swiftly, and at times breaks moving fly wheels or emery wheels into dangerous fragments. Usefully applied, centrifugal force extracts water from wet sugar or chemicals placed in a perforated cylinder (Figure 543). Since a greater force acts upon heavy bodies than upon light ones,

whole milk put into a cylinder revolving 10,000 revolutions per minute is separated into the heavier skim milk at the outside of the cylinder and cream at the inside. Chemists use a centrifuge to separate precipitates from filtrates and dairy men use it to test milk (Figure 544). David used the centrifugal force of a whirling sling to hurl a pebble at Goliath.

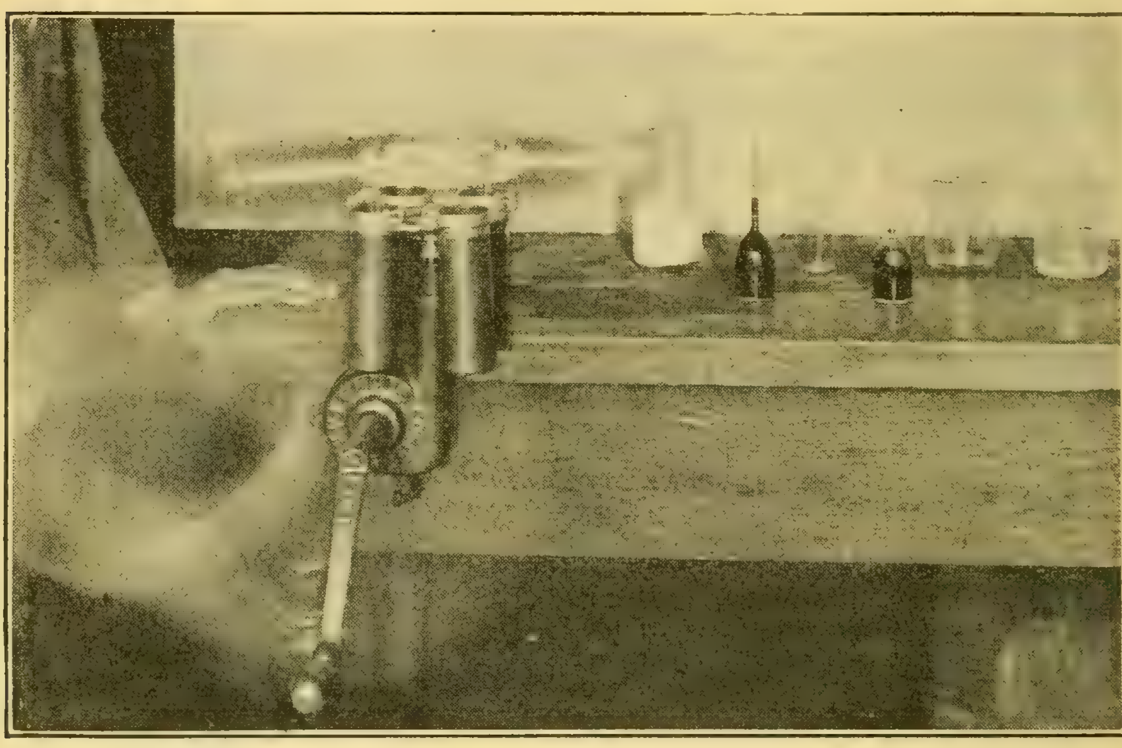

FIGURE 544. — MILK TESTER PHOTOGRAPHED AT REST AND REVOLVING.

The milk is placed in long-necked bottles, shown on the table, and these are set in the four hinged buckets, shown in a vertical position on the centrifuge. When these are rapidly rotated, they assume the position shown in the horizontal blur above. The milk settles to the bottom, and the cream comes up in the neck, which is nearer the center of rotation.

Centrifugal force acting on our earth and the other planets keeps them from falling into the sun, since the gravitational force acting between the sun and the planets is counterbalanced by the outward centrifugal reaction. The flattening of the earth is a probable result of its rotation. There are several experiments to show the effect or the application of this interesting and important force.

EXPERIMENT 141. — Fasten a stout rubber band to a weight that will stretch it only a little. Hold the other end of the elastic band in your hand and whirl the weight rapidly in a circle. *What happens to the rubber band? What force acts upon it? What force acts to keep the weight from flying out from its circular path?*

A whirling table with the usual accessories may be used to show that heavy bodies are whirled farther from the center of rotation than light ones; that heavy balls suspended vertically from a vertically whirling support tend to rise so as to rotate horizontally; and that a body with elastic sides tends to become flattened at the poles of its axis of rotation (Figure 545).

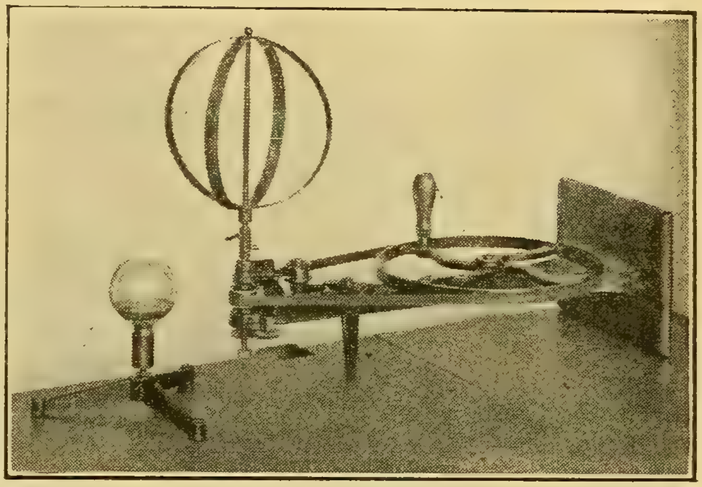

FIGURE 545. — Centrifugal force flattens the metal hoops, when they are rotated. The heavy mercury in the flask becomes a band around the widest part of the flask, with the lighter water forming another band within it.

372. Inertia in Rotating Bodies. — When a body is so acted upon by a centrifugal force that it overcomes the centripetal force, *the body ceases to be acted upon by either force.* This happens if a stone, whirled on a string, breaks the string. The stone, freed from external forces, continues to move in the direction given to it by the force before the string broke. This direction of motion is a tangent to the circular path in which it had been traveling. Thus it is inertia, and not centrifugal force, which causes a rotating body to move off at a tangent to its previous motion.

373. Measurement of Centripetal Force. — Since centripetal force acts toward the center of a circle of rotation,

this force produces an acceleration toward the center. This acceleration is equal to the square of the circular speed ($\mathbf{v}$) divided by the radius of the circle, $\mathbf{a} = \frac{\mathbf{v}^2}{\mathbf{r}}$. But $\mathbf{f} = \mathbf{ma}$ (§ 345). Substituting for $\mathbf{a}$ its value, $\mathbf{f} = \frac{\mathbf{mv}^2}{\mathbf{r}}$. When $\mathbf{m}$ is in pounds and $\mathbf{v}$ in ft/sec and $\mathbf{r}$ in feet, $\mathbf{f}$ will be expressed in poundals, which may be changed to pounds by dividing

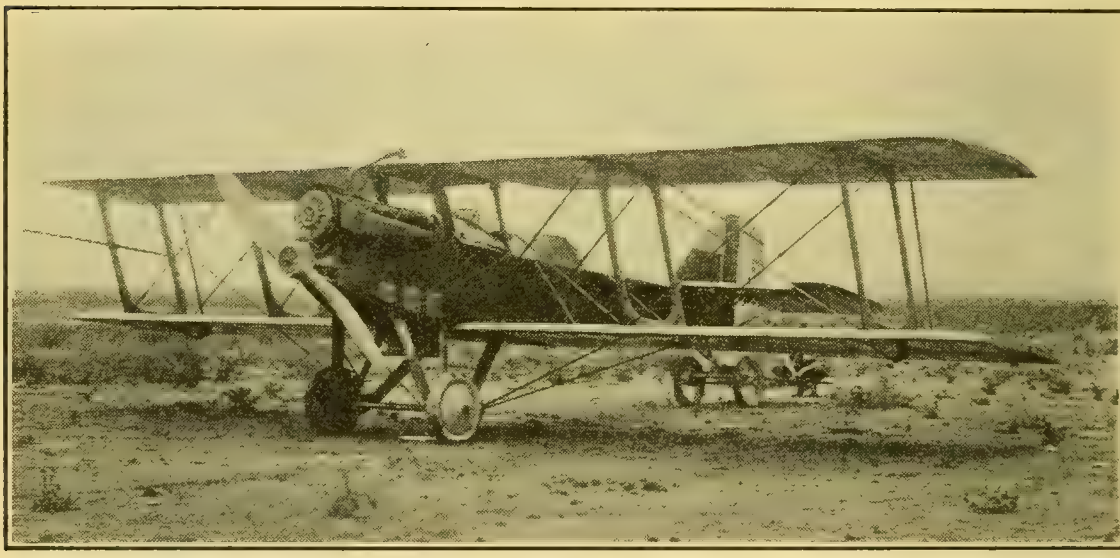

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FIGURE 546. — In this picture of the airplane find the propeller, wings, horizontal and vertical rudders. Note the shape of the wings, the shape and direction of the wing braces, and the wheels for landing and rising.

by 32. If the corresponding values are in grams and centimeters, $\mathbf{f}$ will be expressed in dynes, which may be converted into grams force by dividing by 980. Centrifugal force, being a reaction to centripetal force, is always equal to it, and can be calculated by the same equation.

374. Airplane. — The airplane provides many interesting applications of the principles considered in the foregoing chapter. Its development was foreseen by philosophers centuries ago. The fact that air in motion would support kites and the fact that birds did not depend upon the buoy-

ancy of the air made the airplane thinkable at least. The flight of man in heavier-than-air machines simply waited for the construction of an engine of great power but of little weight. The gasoline engine satisfied these conditions and flight was accomplished as soon as the necessary experiments could be performed.

The wings of an airplane are curved or slanted to set at a small angle with the horizontal (Figure 546). The engine drives a propeller, which resembles an electric fan. This propeller pushes a stream of air backward, but the reaction of the air against the blades of the propeller drives the plane forward with an equal force. This forward force gradually overcomes the inertia of the mass of the plane, and the plane moves slowly forward along the ground. The tilted wings, in moving forward, tend to push the air forward and downward; the reaction of the air against the wings tends to move them upward and backward. The backward motion is prevented by the drive of the propeller, but the upward component of the air's reaction (Figure 547) increases as the speed of the plane increases until gravity is counterbalanced by this upward component and the plane rises in the air. The faster the plane moves forward, the greater the upward component and the more rapidly the plane can ascend. The plane in air must maintain a speed great enough to make the upward component of the air reaction equal the force of gravity.

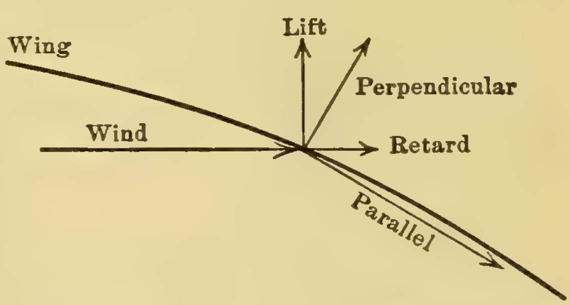

FIGURE 547. — FORCE DIAGRAM OF AN AIRPLANE.

The perpendicular component of the force of the air is resolved a second time to show how the rush of air lifts the plane.

Changing the direction of the plane either vertically or

horizontally is accomplished by another reaction of the air. To turn the machine horizontally to the right, a vertical rudder at the rear of the machine is turned to the right. This rudder causes a greater air pressure against its front surface than exists against the rear surface. This pressure turns the rear of the plane to the left and the front end to the right. A horizontal rudder, tilted up or down, turns the nose of the machine up or down in the same manner.

SUMMARY

Motion may be either translatory or rotary or a combination of these two motions.

Forces acting in the same straight line produce an effect equal to their **sum** if they act in the **same** direction, or to their **difference** if they act in **opposite** directions.

A **resultant** is a single force that will produce the same effect as two or more given forces. An **equilibrant** is a single force that will counterbalance a given force or forces.

When two forces act at an angle, their resultant is proportional to the diagonal of a parallelogram constructed on the two forces, drawn to scale, as sides. The direction of the resultant is indicated by the diagonal.

When three or more forces are in equilibrium about a single point, the resultant of all the forces is equal to zero; the resultant of all but one of the given forces is equal and opposite to the remaining force.

The determination of the resultant of angular forces is known as the **composition of forces. The resolution of forces** is the determination of the effects of a given force in two given directions.

The moment of a force is its ability to produce rotation about a given axis or fulcrum. The moment of a force **is calculated** by multiplying the units of the force by the units of perpendicular distance from the line of the force to the fulcrum.

A body acted upon by any number of parallel forces is in equilibrium if the sum of the forces in one direction equals the sum of the forces in the other direction, and if the sum of clockwise moments equals the sum of counterclockwise moments.

A lever is a rigid bar used to overcome a resistance by a force acting in such a manner as to produce rotation. The relation between the required force (effort) and the resistance is determined by the principle of moments.

The Law of Universal Gravitation states that all bodies in the universe attract each other with force that varies directly as the product of the masses of the bodies and inversely as the square of the distance between their centers.

The period of a **pendulum** is dependent upon the length of the pendulum but not on its mass or on its arc.

The stability of a body is its tendency to retain a given position against the tipping effect of forces applied to it. The stability of a body is measured by the amount of work required to make the body take a new position. Stability depends upon weight, the location of the center of gravity, and the area of the base upon which the body rests.

There are three kinds of equilibrium: stable, unstable, and neutral.

A body in **circular motion** is acted upon by a pair of equal reacting forces; **centripetal** force tends to accelerate the body toward its center of rotation, and **centrifugal** force tends to move the body outward from its center of rotation.

EXERCISES

(The solution of each problem should be accompanied by a diagram in which the forces and velocities are correctly represented.)

1. Find the resultant of the following combinations of forces if they act in the same direction and if they act in opposite directions: 10 lbs and 15 lbs; 16 lbs and 20 lbs; 24 lbs and 36 lbs.

2. Determine the different resultants that may be obtained from three forces of 8, 12, and 20 lbs respectively, if they act on a single point in the same straight line (not necessarily in the same direction).

3. A boy riding in a train moving 40 mi/hr drops a ball. Where will the ball strike with reference to the boy? If he throws the ball forward with force enough to give the ball a velocity of 20 mi/hr, what will be the speed of the ball with reference to the boy? What will be the speed if he throws it backward?

4. Two boys riding in the train mentioned above throw the ball back and forth with a velocity of 20 mi/hr. Determine the velocity of the ball at various times with respect to each boy and with respect to a point outside the train.

5. A river steamer has a velocity of 12 mi/hr in still water. If the average velocity of the stream is 2 mi/hr, find the velocity of the boat when it heads directly upstream; downstream; and directly across stream.

6. A football is kicked by two boys at the same time. One kicks toward the northeast with a force of 30 lbs, the other toward the west with a force of 15 lbs. In what direction will the ball move and what is the effective force moving the ball?

7. Three forces of 6, 8, and 10 lbs act upon a body from the north, east, and northwest respectively. Find the approximate direction and value of the resultant of these forces; of their equilibrant.

8. A telegraph pole is held erect by a slanting guy wire which makes an angle of 30° with the pole. The wire is under a tension of 800 lbs. What is the component of this tension that holds the pole erect? What does the vertical component do?

9. The handle of a lawn mower is held at an angle of 40° with the earth and the mower is pushed with a force of 24 lbs. Determine horizontal and vertical components of the force.

10. A sled is drawn by a rope which makes a 30° angle with the horizontal. Find the useful and the useless component of a force of 10 lbs along the rope.

11. A child who weighs 72 lbs is in a swing pulled back by a playmate until the ropes of the swing make an angle of 20° with the vertical. How much force must be exerted along the swing ropes and by the playmate to keep the swing in this position?

12. A load of 300 lbs rests on a plank 10 ft long, one end of which is elevated to a height of 3 ft. What is the component of the weight pressing perpendicularly against the plank? What force will be required to equal the component parallel to the plank and to keep the weight from sliding down the plank?

13. A person weighing 125 lbs sits in a hammock, which is attached to hooks so that the hammock ropes make a 60° angle with the vertical. Find the tension in the ropes.

14. If a person sits in the hammock referred to in the previous question, and causes a tension of 200 lbs in the ropes, find the force that tends to pull each post into the earth, and the pull that tends to draw posts inward.

15. Make a force diagram showing the weight of a kite, the pull of the string, and the force of the wind. What relation does the resultant of any two of these forces have to the third force?

16. Explain the difference between the flight of airplanes and that of dirigibles.

17. The tilted wing of an airplane is driven horizontally through the air (Figure 547, page 623). Show the horizontal motion of the air with reference to the wing and indicate the component of the force of the air that supports the airplane.

18. Which requires stronger ropes to support a given weight, a hammock or a swing?

19. Explain why a tightly stretched string breaks easily when a small force is exerted against it at right angles to its center. Would the string break as easily if it were not so tight?

20. A steel bar is perfectly straight before being supported at its two ends only. What shape do you think it to be in this position? What force makes it take this shape? What property of the steel allows it to take this shape without breaking?

21. It is 5 ft from the axle of a wheelbarrow to the place where a laborer takes hold of the handles. It is 2 ft from the axle to the center of gravity of the load in the barrow. Find the effort required to lift 200 lbs in the barrow.

22. When 200 lbs of cement are placed in the barrow, the center of gravity is only 1 ft from the axle. Find the force required to lift the handles of the barrow when thus loaded.

23. The barrow itself weighs 40 lbs and its center of gravity is 2 ft from the axle of the wheel. It is loaded with cement as before. Find the moment of the weight of the barrow, the moment of the weight of the cement, and the force required to lift the handles.

24. In each of the three questions preceding, find the amount of weight supported by the wheel of the barrow.

25. A fireman lifts 20 lbs of coal in a shovel, the center of gravity of the coal being 4 ft from his left hand. His right hand is betweeen the coal and his left hand, and 3 ft from the left hand. Considering his left hand as a fulcrum, how much effort must his right hand exert to lift the coal?

26. The right hand of a snow shoveler is 3 ft from his left hand and 2 ft from 15 lbs of snow on the shovel blade. Find the force that must be exerted by each hand when the snow is lifted. Make a diagram showing the direction of all forces.

27. A lineman gripping a pair of pliers with a force of 50 lbs at an average distance of 6 in from the rivet of the pliers cuts a wire at a distance of $\frac{1}{2}$ in from the rivet. What is the resistance offered by the wire?

28. Shears used to cut sheet metal have long handles and short blades; those used to cut paper have short handles and long blades. Why should there be this difference?

(In solving the following problems, consider one support as the fulcrum and the other as the effort.)

29. A and B carry a weight on a pole between them. Where must the weight be placed so that A shall carry one half of the load? One third of the load? Two fifths of the load?

30. A 3-ton truck is 20 ft from one end of a 60-foot bridge. What moment does the truck produce about the nearer end? What moment must be produced about this end by the force upward at the other end of the bridge? What force must be exerted at the farther end of the bridge? What exerts this force?

31. A 4-ton truck is 10 ft from the north end of a 50-foot bridge when a 2-ton pleasure car is 20 ft from the south end. Calculate the pressure in addition to the weight of the bridge which is caused by these weights on each support of the bridge.

32. A meter stick is supported at the ends by spring balances. A 200-gram weight is hung at the 35-centimeter mark, and 300 g at the 80-centimeter mark. The stick itself weighs 150 g. What force stretches each balance?

33. A coal truck measures 16 ft. between the centers of its front and rear wheels. Its weight of 2 tons is centered 6 ft from the front wheels, but its load of 4 tons is centered 4 ft from its rear wheels. How much of the combined weight of truck and load is supported by the rear wheels?

34. A meter stick, pivoted at the center, has 100-gram weights hung at the 15-, 35-, 60-, and 95-centimeter marks. What force at the 20-centimeter mark will keep the stick from turning?

35. Observant sailors can tell whether a boat is loaded with iron ore, grain, or lumber, by noting how quickly the boat rights itself after rolling. What causes the difference?

36. A salesman's trunk is 4 ft long and 2 ft $\times$ 2 ft square. When uniformly packed, it weighs 200 lbs. How far above the floor is its center of gravity when resting on a 4 $\times$ 2 face? If the trunk is tipped up on end, what is the highest point reached by the center of gravity while being tipped? How much work is done in tipping the trunk on end?

37. How high is the center of gravity when the trunk is standing on end? How much is the center of gravity raised when the trunk is tipped back on one side? How much work is done when the trunk is tipped back on one side?

38. Give three applications of centrifugal force in useful processes. Why is centrifugal force more commonly spoken of than centripetal force?

CHAPTER XXVIII

WORK AND SIMPLE MACHINES

375. Work. — When a man lifts a block of ice into the ice box, we know that he is doing work. To raise the ice he has to use force to overcome the pull of gravity upon it. The heavier the cake of ice, the more work he has to do. Similarly, the higher the opening into which the ice is put, the greater is the work that he must do. The total work that the man does is the product of the force necessary to overcome the pull of gravity $\times$ the vertical distance through which the block is lifted.

Work is done in rowing a boat, pushing a wheelbarrow, pulling a sled, hammering a nail, scrubbing a floor, in wringing out clothes, and in walking up stairs. The connecting rod does work on the driving wheels of a locomotive, and a propeller does work in pushing a boat through the water. In all these cases, resistance to motion is being overcome by a force that produces movement or displacement. In propelling a boat, the water has to be pushed aside and the friction between the water and the sides of the boat overcome. The blow of the hammer makes the nail press apart the fibers of the wood and overcome the friction between the nail and the wood. In order to have work done, motion or displacement must be produced. A man holding up a weight or pushing against a wall is not doing work, although he may become very tired. Neither does a weight suspended by a rope accomplish work, although it pulls steadily downward

upon the rope. Force exerted without producing motion does not do work (Figure 548).

On the other hand, motion which continues without the application of force does not constitute work. A horse pulling a load on an asphalt pavement does less work than he would in pulling the same load along a dirt road. Still less work is done in pulling the same load on ice, because less force is applied. The earth continues in its path without the expenditure of work, because it meets no resistance and therefore requires no force. We see, then, that work involves two factors: *force,* and *motion* in the direction of the force. Work is measured by the product of a force (F) and the distance (d) through which the force is exerted:

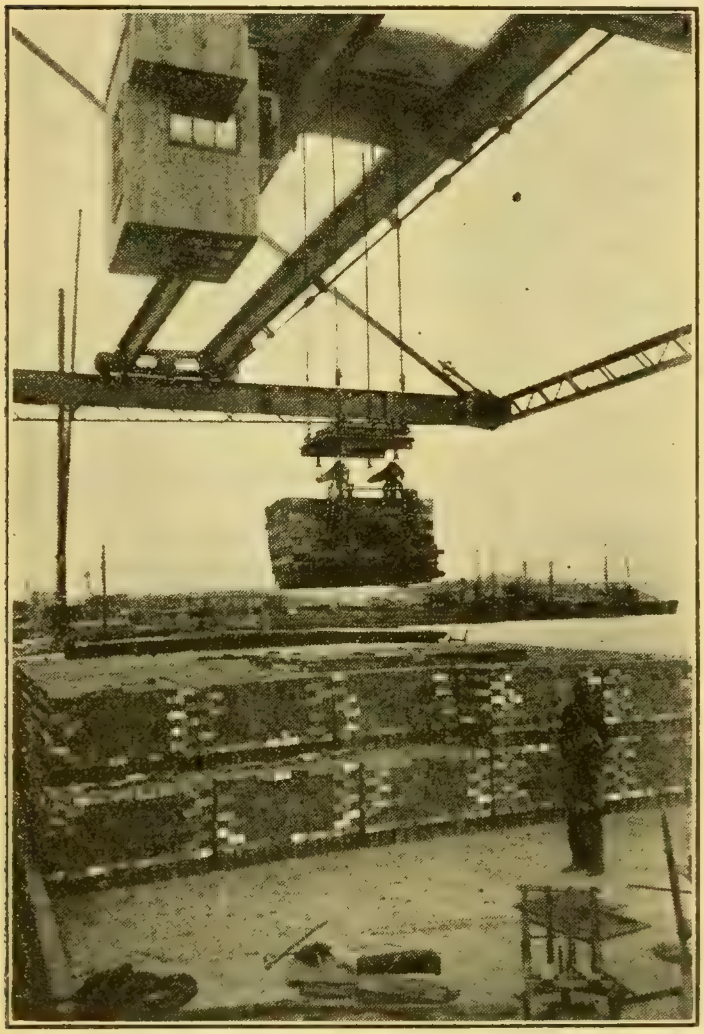

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FIGURE 548. — Force is exerted but no work is done when a weight is supported motionless in air.

$$\text{Work} = Fd.$$

376. Units of Work. — Since the amount of work is equal to the product of the force by the distance, the units for measuring work are derived from the units of force and dis-

tance. In the British system, the unit of work is the *foot-pound.*

A foot-pound is the amount of work done when a pound force acts through a distance of one foot.

If we lift a pound weight 1 foot, we have done a foot-pound of work (Figure 549). Lifting the weight 2 feet calls for 2 foot-pounds of work. Lifting 5 pounds of sugar 2 feet up from the counter involves 10 foot-pounds of work. But the work done in sliding the sugar 2 feet along the counter is much less than 10 foot-pounds, for the only resistance to be overcome is the friction between the bag and the counter. This resistance is much less than 5 pounds.

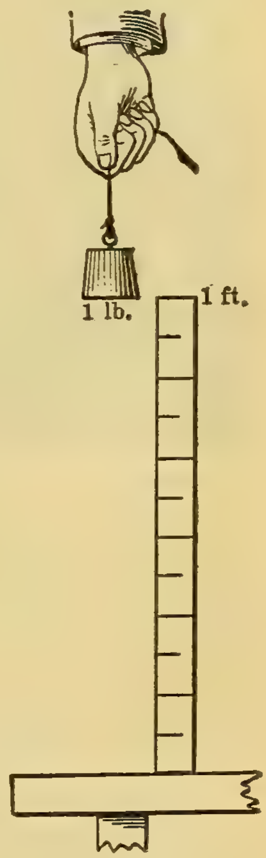

FIGURE 549.— One *foot-pound* of work is done when a one-pound weight is lifted one foot.

In the Metric System, the *gram-centimeter* is the unit of work. This means the amount of work done when a gram force acts through 1 centimeter. The kilogram-meter is also used as a unit of work.

377. Inclined Plane.— Truckmen, in loading a heavy object on a truck, find it easier to roll it up an inclined plank or skid, than to lift the object vertically (Figure 550). If the object to be loaded weighs 200 pounds and the platform of the truck is 4 feet from the ground, at least 200×4, or 800 foot-pounds of work must be done to get the object on to the truck. The truckman, let us say, uses a skid 10 feet in length and rolls the object up this distance, which is more than twice the vertical distance that the object would have to be lifted. In what way, then, is the skid an advantage to the truckman? The study of a simple ex-

periment with an inclined plank or inclined plane, as we say in Physics, may answer the question.

EXPERIMENT 142. — Let us use an inclined plane 4 feet long with its raised end 2 feet above the table (Figure 551). The weight to be raised is a roller weighing 2 pounds. For measuring the force or pull required to move the roller up the plane, a spring balance will serve. It is attached by a stout string to the roller. The reading on the spring balance gives the pounds force required, provided we are careful to keep the balance and the connecting cord parallel to the surface of the plane and also to pull the roller up the plane at a uniform rate. We find that a force of $1\frac{1}{4}$ pounds is needed for the pull. Since the roller is pulled the length of the plane, 4 feet, the work done is:

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FIGURE 550. — LOADING A 16-TON CHEESE.

Because gravity is overcome slowly as the weight is moved up the plane, a heavy weight can be moved up the plane by a small force.

$1\frac{1}{4}$ pounds (force) $\times$ 4 feet (displacement) = 5 foot-pounds.

The roller, however, has been raised but 2 feet vertically above the table. The work required to raise this 2-pound roller vertically is:

2 pounds (force) $\times$ 2 feet (displacement) = 4 foot-pounds.

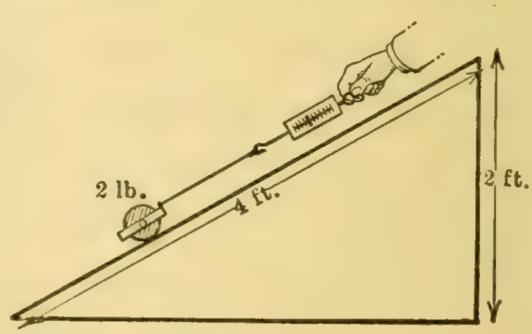

FIGURE 551.

Comparing results, it is seen that 5 foot-pounds of work have been done with the plane to accomplish 4 foot-pounds of *useful* work needed to lift the roller 2 feet above the table. The 1 foot-pound of work that was apparently lost was used

in overcoming friction mainly between the roller and the plane. Since we cannot make machines to run without friction, the inclined plane in practice is like other machines in that we put more work into it than we can get out.

However, the spring balance told us that we were using only $1\frac{1}{4}$ pounds of effort to raise a 2-pound roller. The effort required with the plane is less than is needed to lift the roller vertically. It must be remembered, however, that to get to a height of 2 feet the roller had to be pulled 4 feet along the plane. The less effort meant a greater distance.

Similarly, the inclined plank enabled the truckman to use much less effort than a 200-pound force in rolling the object up into the truck, although he had to apply his effort over a greater distance than if he had lifted the object directly.

The inclined plane enables work to be done with less effort. The smaller the force (effort) used to do a given amount of work, the greater must be the distance through which the force acts.

This is why a horse uses less effort on a gradual incline than on a steep grade in pulling a load to the top of a hill. The distance may be shortened by using a steep grade, but the effort is much increased. Hence in building roads and railways, engineers try to have as easy grades as possible. To get over mountains, devices such as zigzags and loops have to be used to secure gradual inclines that permit loads to be pulled up with reasonable effort (Figure 552).

378. Law of the Inclined Plane. — If we could get perfect apparatus that did away with all friction, we should find that only 1 pound of force would be needed to pull the 2-pound roller up the plane of Figure 551. That is, 1 pound (force) $\times$ 4 feet (distance) gives 4 foot-pounds of work done. This is just equal to the foot-pounds required to lift the 2-pound

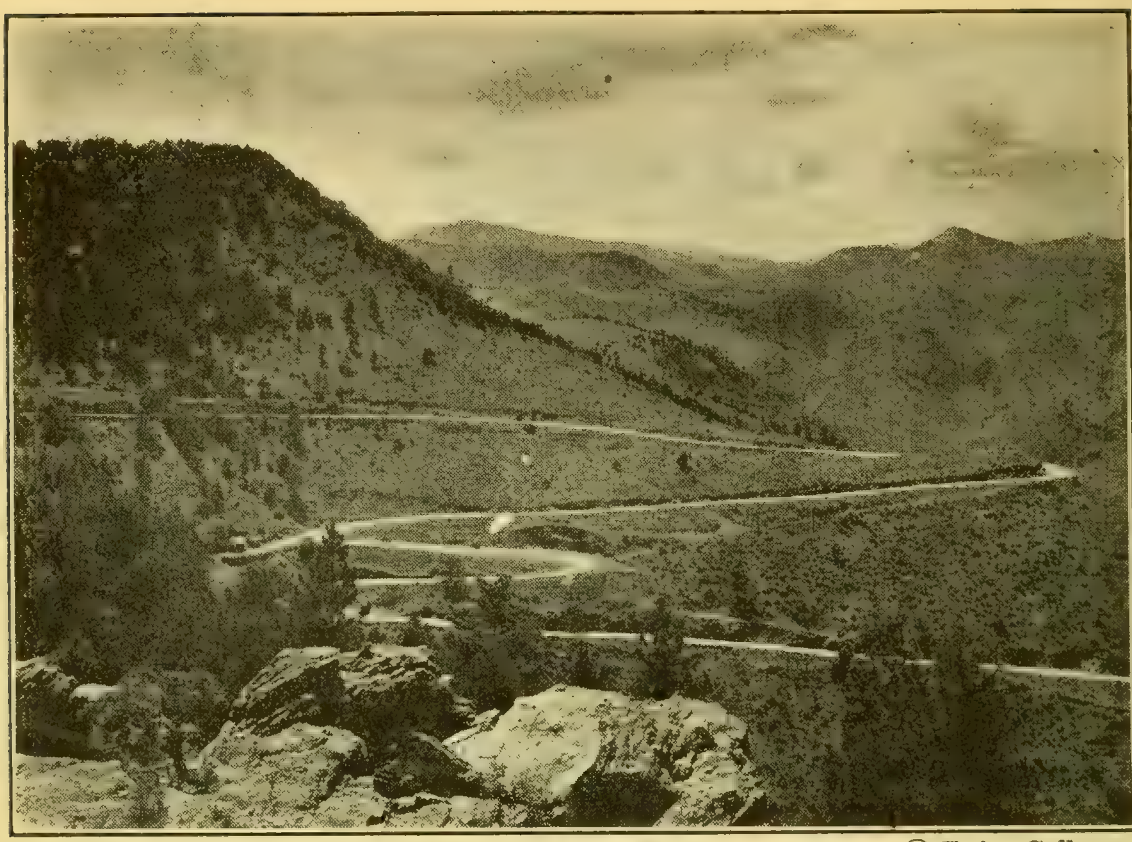

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FIGURE 552. — LARIAT TRAIL, COLORADO.

The winding road permits a small force to move a heavy load slowly toward the summit.

roller vertically 2 feet, which is the height of the plane. Expressing the equality in the dimensions of the inclined plane:

force × length of plane = weight × height of plane.

Fom these two equal products, we can derive the proportion:

$$\frac{\textbf{weight}}{\textbf{force}} = \frac{\textbf{length of plane}}{\textbf{height of plane}}.$$

This is known as the *Law of the Inclined Plane.* Using the term *resistance* for the weight and the term *effort* for the force, the law is often expressed:

$$\frac{\textbf{resistance}}{\textbf{effort}} = \frac{\textbf{length of plane}}{\textbf{height of plane}}.$$

This equation is useful in finding the value of one of the quantities when we know the value of the other three. Take the case of a truckman pushing a 1000-pound safe up a 20-foot skid to the platform of a truck 2 feet above the sidewalk. The weight (resistance), the length of the plane, and the height of the plane are known. The force (effort) that the truckman will have to exert is unknown but can be found, since:

1000 (resistance) × 2 (height of plane) = effort × 20 (length of the plane). Then, 2000 = 20 × the effort; and the effort is 100 lbs. The truckman, therefore, would have to exert 100 lbs force to push the safe in case the plane was an ideal one without friction.

379. Wedge. — The wedge in its simplest form, as in a chisel, is a movable inclined plane, which overcomes a large resistance at right angles to the applied effort. The effort is applied to the base of the plane and the resistance has its effect on the slant side. The wedges used to split logs are movable double-inclined planes. They may also be regarded as two planes placed base to base (Figure 553). Knives, nails, pins, needles, and many other cutting or piercing instruments are forms of the wedge. Wedges hold hammer heads tightly on the handles. They are also used to raise heavy weights, as in the setting up of heavy machinery.

FIGURE 553.—The wedge is usually two inclined planes placed base to base.

Owing to the fact that impulsive rather than steady forces are generally used to drive wedges, it is not easy to give a mathematical statement that expresses the advantage of the wedge. In general, the sharper the angle of the wedge, the less the effort required to make it overcome a given resistance.

380. Law of Work. — When work is done with a machine like the lever or the inclined plane, the resistance in one part of the machine must be overcome by the effort in another part. In the case of the little roller on the inclined plane (§ 377), the work done by the effort was equal to 5 foot-pounds, while only 4 foot-pounds of work was done on the roller.

Friction was responsible for the work put into the machine being more than the useful work accomplished by it. By using more perfect apparatus that would reduce the friction, the work put into the machine would be lessened and approach nearer to the useful work done, or the "work output." In a perfect or *ideal* machine:

$$\textbf{work input} = \textbf{work output.}$$

This equality is the *Law of Work.*

In *actual* machines the work input is always greater than the useful work output. To make this difference between the work input and the work output as small as possible is always the aim of machine designers.

381. Mechanical Advantage. — *In a perfect machine,* the ratio of the resistance to the effort is called the *mechanical advantage* of the machine:

$$\frac{\textbf{resistance}}{\textbf{effort}} = \textbf{mechanical advantage.}$$

If a frictionless 12-pound roller is pulled up an inclined plane by a 4-pound force, the mechanical advantage of the plane is 3, a *number* obtained by dividing the resistance by the effort.

In § 378, it was stated that

$$\frac{\textbf{resistance}}{\textbf{effort}} = \frac{\textbf{length of plane}}{\textbf{height of plane}}$$

Hence the mechanical advantage of any inclined plane can be found by dividing the length of the plane by the height of the raised end. A plane 8 feet long with the raised end 2 feet from the ground has a mechanical advantage of 8/2, or 4.

When machines enable one to use a lesser effort to overcome a greater resistance, it should be remembered that this advantage is gained at the sacrifice of distance or of speed. Thus in the inclined plane just mentioned, a man can easily roll a heavy barrel of sugar up the plane, but he has to exert force over a distance of 8 feet to lift the barrel a vertical distance of 2 feet.

QUESTIONS

1. Define *work*. Give five examples of the accomplishment of useful work in the scientific sense.

2. Give two examples in which a man is not doing work, although he is using his strength.

3. What two factors must be known in order to calculate work? Give the equation.

4. Name two units by which work is measured, and define each.

5. How much work is done in lifting a 50-pound box 10 ft? Is the same amount of work done in sliding it 10 ft along the floor?

6. How much do you weigh? How much work do you do in walking up a flight of stairs 12 ft high?

7. Compare the force used in pulling a car up an inclined plane with the force necessary to lift it vertically to the top of the plane (neglect effect of friction). Why is this true?

8. Why does an automobile road wind around a hill instead of taking the shortest route to the top?

9. State the law of the inclined plane, using the terms *resistance* and *effort*.

10. A box weighing 60 lbs is pulled by a rope up an inclined plane 12 ft long and with its upper end 3 ft from the ground. Make a labeled diagram of the plane, showing the effort and its distance, and the resistance and its distance.

11. What is the wedge in its simplest form? Where is the effort applied to the wedge? Where is the resistance effective?

12. Give examples of the wedge in practical use.

13. State the *Law of Work* for an ideal machine. Why does not this equality hold true for actual machines?

14. What is meant by the mechanical advantage of an ideal machine? Express this idea in equation form.

15. How may the mechanical advantage of an inclined plane be found? State this in the form of an equation.

16. What is the mechanical advantage of an inclined plane 20 ft long and 2 ft high? 4 ft high? 5 ft high? 8 ft high?

17. In each case in Question 16, determine the force parallel to the plane required to hold on the plane a barrel weighing 160 lbs.

18. In each case in Question 16, determine the weight that could be held on the plane by a force of 50 lbs parallel to the plane.

382. Lever. — The lever is a rigid bar free to move about a fixed point called the *fulcrum*. The seesaw is an example of the lever encountered in our childhood days. The middle point at which the plank is supported is the fulcrum. When

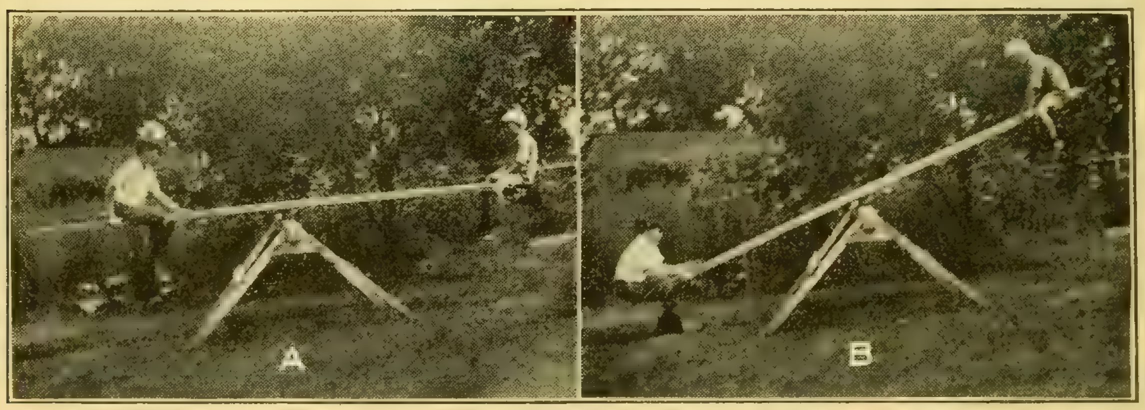


FIGURE 554. — The same work is done in lifting the heavy boy a short distance as in lifting the lighter boy a long distance.

one child is heavier than the other, the heavier one has to sit nearer the middle in order to have the plank balanced in a horizontal position (Figure 554, A). In the case when both children are sitting at the ends of the plank, the fulcrum must be moved nearer the heavier child. Then the lighter

child may feel that he is swung to a perilous height by the weight of the heavier child, who, however, thinks that he is not getting much of a swing (Figure 554, B). All of this is in accordance with the principle of work. The weight of the heavier child is the effort, and the distance that he moves vertically is the effort distance; while the weight of the lighter child is the resistance and his vertical movement is the resistance distance. The effect of the friction and of the weight of the plank are so small that we may disregard them in the statement of the principle:

resistance × resistance distance = effort × effort distance.

If a 75-pound boy is lifted 8 feet from the ground, a 120-pound boy must come down 5 feet:

FIGURE 555.—The crowbar gives the man a mechanical advantage equal to the number of times the long arm of the lever is as great as the short arm.

$$75 \times 8 = 120 \times 5.$$
$$600 \text{ ft-lbs} = 600 \text{ ft-lbs}$$

Another example of the lever is the crowbar, familiar in its use for moving heavy weights (Figure 655). A smaller object usually serves for the fulcrum. It will be noted that the resistance arm is much shorter than the effort arm. This is why a man with a force of a few pounds can pry up a heavy stone weighing many pounds. The advantage to the workman depends upon the relative lengths of the resistance and

the effort arms of the lever. The mechanical advantage of the lever may be stated:

$$\frac{\textbf{length of effort arm}}{\textbf{length of resistance arm}} = \textbf{mechanical advantage.}$$

The seesaw and the crowbar are examples of levers of the first class in which the fulcrum is between the effort and the resistance. This and the other classes of levers are studied in relation to the principle of moments in Chapter XXVII. *Whatever the class of lever, however, the work output equals the work input.*

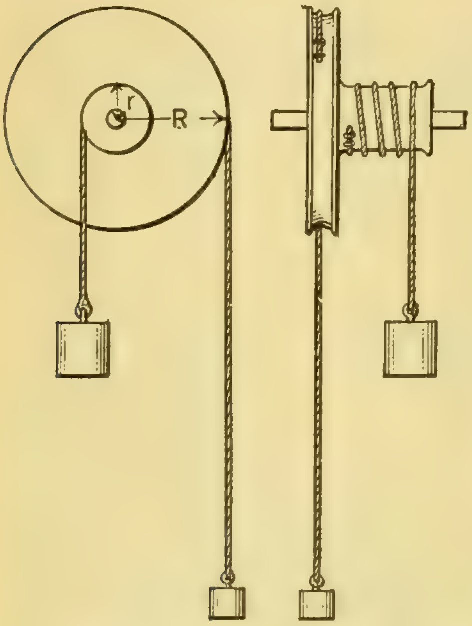


FIGURE 556. — Small forces acting through the large distance, R, balance large forces acting through the small distance, r.

383. Wheel and Axle. — This simple machine is a modified form of the lever. The effort is applied to the circumference of a wheel which turns the axle so as to raise a weight (Figure 556). The effort arm is R and the resistance arm is r. When the effort arm is 4 times as long as the resistance arm, a 1-pound force will raise a 4-pound weight, or a 5-pound force will lift a 20-pound weight.

According to § 361, the effort × the effort arm R must equal the resistance (weight) × the resistance arm r. Since R is the radius of the wheel and r the radius of the axle, then:

effort × radius of the wheel = resistance × radius of the axle.

The effort force moves through a greater distance than the resistance, since a smaller force balances a weight greater

than itself. The resistance (disregarding friction and the weight of the machine) can be as many times as great as the effort force as the radius of the wheel is times as great as the radius of the axle. This states the mechanical advantage of the wheel and axle:

$$\text{mechanical advantage} = \frac{\text{radius of the wheel}}{\text{radius of the axle}}.$$

Since with both wheel and axle, the diameter of each is twice its radius, and the circumference in each case is 3.1416 times its diameter:

$$\text{mechanical advantage} = \frac{\text{diameter (or circumference) of wheel}}{\text{diameter (or circumference) of axle}}.$$

When a 5-pound force lifts a 20-pound weight, the radius, the diameter, or the circumference of the wheel is 4 times as great as the corresponding dimension of the axle.

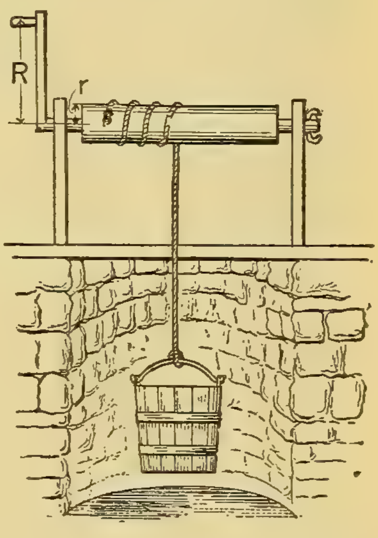


FIGURE 557. — The windlass is one form of the wheel-and-axle type of machine. Its mechanical advantage is R divided by r.

The windlass, used in raising water from a well (Figure 557) or from a street excavation, is a wheel and axle in which a crank serves as the wheel. The capstan for raising the anchor of a ship has several bars in place of the wheel. The outer ends of the spokes on the steering wheel of a motor boat make the actual wheel of such a wheel and axle. The hoisting mechanism of a derrick consists of a double wheel with an axle. Force is applied to the smaller wheel, which passes on its motion to the larger wheel by means of a cog-wheel. In lathes, shafting, and machinery in general, the wheel and axle is

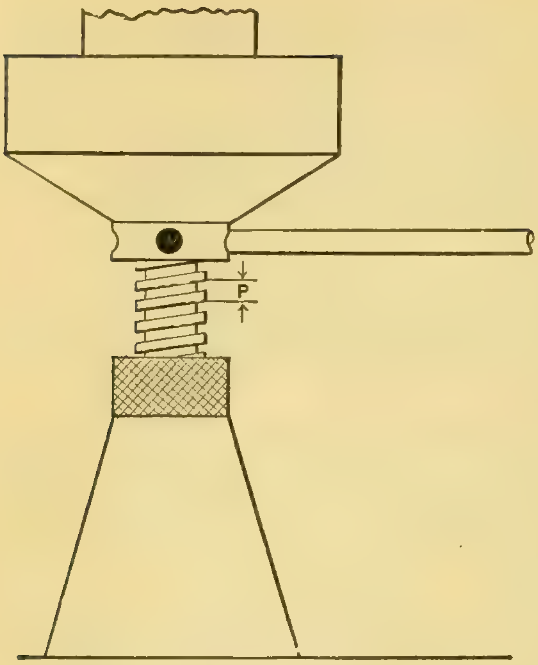


FIGURE 558. — The mechanical advantage of the jackscrew is very large because the effort must move through the circumference at the end of the bar in order to move the resistance the *pitch* of the screw, *P*.

extensively used. Clockwork consists chiefly of wheels and axles.

384. Screws. — When a house is to be lifted off its foundations, a jackscrew (Figure 558) is used. This consists of a cylinder, around which runs a thread that fits into a corresponding groove in a stationary base. When the cylinder is turned once around, it moves upward (or downward) a distance equal to the vertical distance between two successive threads. This vertical distance is known as the *pitch* of the screw (Figure 559). In its practical uses, the screw is turned by a bar which fits into the cylinder. A small force at the end of the bar enables the screw to exert an enormous lifting force through a very short distance. To get this mechanical advantage, the end of the bar in making one complete turn must travel, according to the principle of work, a much greater distance than the pitch of the screw. *The mechanical advantage of the screw is the ratio of the circumference described by the bar to the pitch of the screw.*

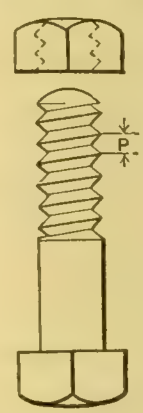
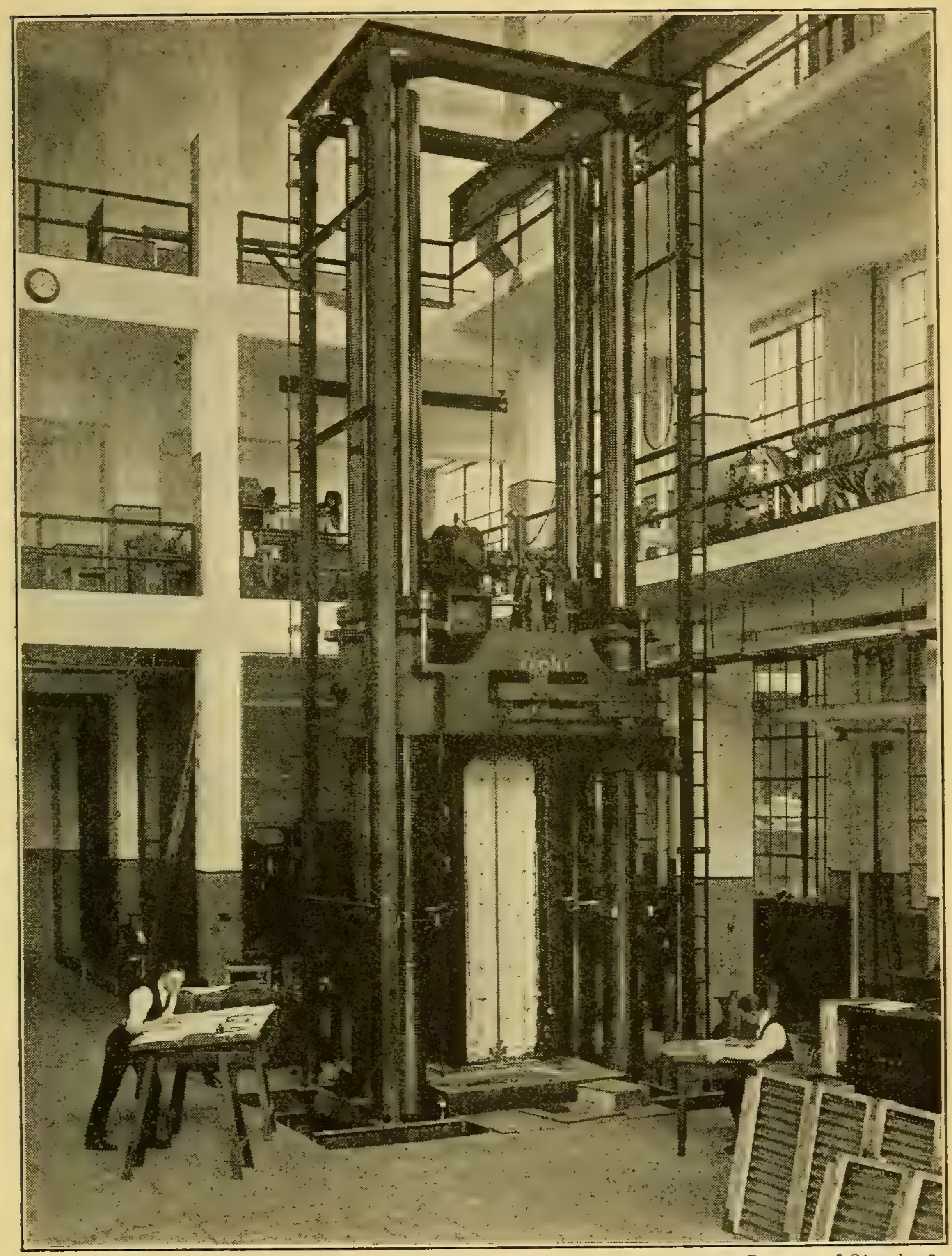


FIGURE 559. — The pitch of a V-thread, like that of a square thread, is from any point on one thread to the corresponding point on the next one.

The screw is really an inclined plane wrapped around a cylinder. The pitch of the screw corresponds to the height of the



Courtesy Bureau of Standards.

FIGURE 560. — TESTING MACHINE AT BUREAU OF STANDARDS.

The machine is shown testing the strength of a large steel beam. Four enormous screws are used to adjust and support the movable member of this machine. The testing force is exerted by a hydraulic press, the large piston of which supports the lower plate of the testing machine.

inclined plane, and the circumference of the cylinder corresponds to the base of the plane. When the screw is turned by a lever, as it usually is, the screw and lever is really a combination of an inclined plane with a wheel and axle.

The screw is used in lifting heavy weights and in presses of various kinds, such as the bookbinders' press and the letter press. It is also found in one form or another in many practical machines. An example of screws used to exert great power is found in the testing machine (Figure 560).

385. Pulleys. — The block and tackle makes many heavy tasks easier. With it the farmer pulls stumps from the ground, or he attaches a fork to it and lifts hay or grain from the wagon to the barn loft. The mover gets safes or pianos to the upper stories of buildings, and heavy steel beams are lifted into place as a skyscraper is built. Along the docks some form or combination of the pulley is used to load heavy articles of cargo on ships. A pulley may be fixed, or movable, or, as is usually the case in practice, a combination of these two kinds.

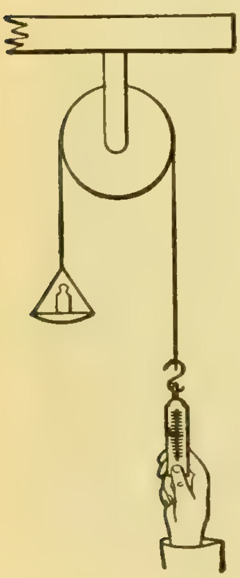


FIGURE 561.

386. Fixed Pulley. — The simplest form of the pulley is the *fixed pulley,* and a simple experiment shows its practical advantage.

EXPERIMENT 143. — A spring balance is used to measure the pull (effort) required to raise the weight in the pan (Figure 561). The pan with its supporting cords is made just equal in weight to the balance.

Raise a 100-gram weight at a uniform rate by pulling down on the hook of the balance, and take the balance reading. This reading is the effort required to raise the weight that was placed in the pan. *How does the distance through which the load (resistance) is moved compare with the distance traveled by the effort in the same time? Compare in amount the load and the effort. What is the mechanical advantage of a single fixed pulley? Why then is it used?*

Disregarding friction, a pull of 25 pounds on one rope of a fixed pulley will raise a 25-pound weight suspended from the other rope. The hand pulling on the rope moves the same distance as the weight moves upward. Not only is the effort equal to the resistance, but the displacement of the effort and the displacement of the resistance are the same. Hence the mechanical advantage of a single fixed pulley is 1. The only real advantage gained is a change in direction. Often this is a great convenience, for it is much easier to raise objects by pulling downward on a rope than it is to lift them, because part of the weight of the man pulling downward is included in the force that he exerts.

387. Single Movable Pulley. — A simple experiment with a single movable pulley will show the particular advantage which leads to its use in combinations of pulleys.

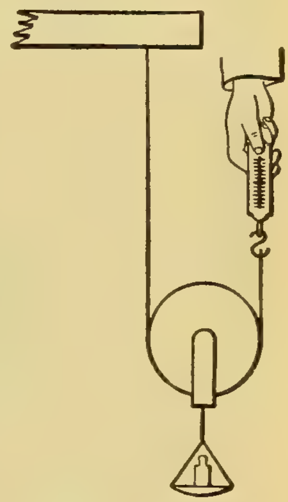


FIGURE 562.

EXPERIMENT 144. — The total load of the single movable pulley in Figure 562 includes the weight of the pan and the weight of the pulley block. Find these two weights. *What is the total load when a 100-gram weight is put on the pan?*

Read on the spring balance the pull needed to raise the total load. *About what fractional part is the pull (effort) of the total load (resistance)? How does the distance through which the resistance moves compare with the effort distance? What is the mechanical advantage of a single movable pulley? What is sacrificed to gain this?*

Disregarding the friction of a single movable pulley, a weight of 60 pounds can be lifted with a pull of 30 pounds. The mechanical advantage, then, is 2. Since the product of the effort × its displacement must equal the product of the resistance × its displacement, the force applied must travel twice the distance that the weight is raised. Thus distance

is sacrificed to make use of an effort which is but half of the resistance.

The mechanical advantage of a single movable pulley is due to the fact that one of the cords supports half of the

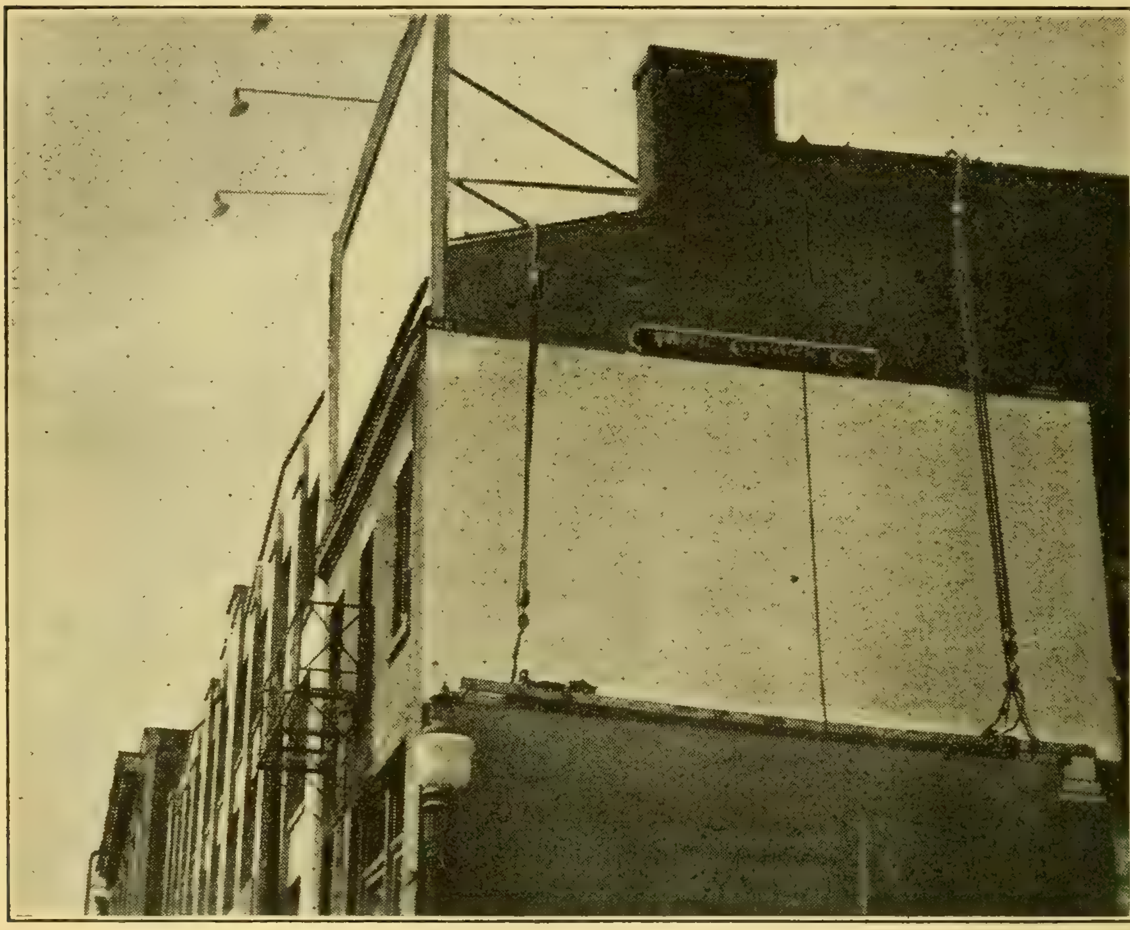
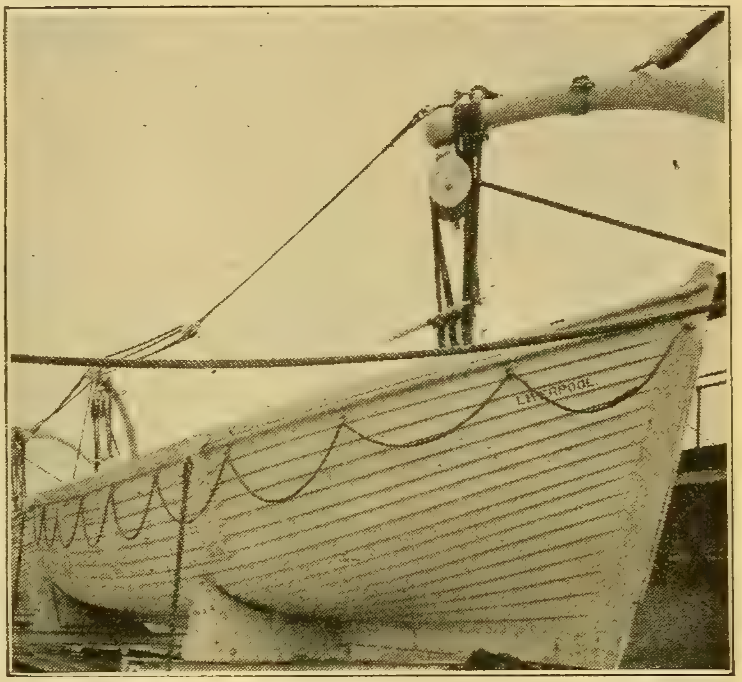


FIGURE 563. — House painters use a combination of pulleys to raise and lower their scaffold. Why is this combination of advantage to them?

load. Thus a force on the other cord equal to half the load is enough to lift the load.

388. Combinations of Pulleys. — House painters raise and lower their scaffolds by the combination of fixed pulleys with movable ones. Such a combination of pulleys (Figure 563) combines the mechanical advantage of each. The single movable pulley requires the effort to be only half the resistance, while the fixed pulley enables the force to act in a direction opposite to that of the movement to be produced.

The most useful form of pulley is the commercial block and tackle. It usually consists of two or more wheels (*sheaves*) on an axle supported in a frame (*block*) for the fixed pulley, connected by ropes (*tackle*) with a movable block of similar construction (Figure 564).



Courtesy Cunard Steamship Co.

FIGURE 564. — ON THE BOAT DECK.

A block and tackle is seen at each end of the lifeboat, with two sheaves in each block.

EXPERIMENT 145. — Two fixed and two movable pulleys are arranged as in Figure 565, *A*. After weighing the movable block with the pan, place a 500-gram weight in the pan. *What is the total load to be raised?*

With a spring balance in a vertical position, take the average of the readings while the load is being (*a*) raised, (*b*) lowered at a uniform rate. *What is the effort required? Compare the distance moved by the effort and by the resistance in the same time.*

What whole number expresses approximately the mechanical advantage? Count the number of cords that support the load. *State the mechanical advantage of such a combination of pulleys in terms of the cords or ropes that support the load.*

Two ways of combining two single fixed pulleys with two single movable pulleys are shown in Figure 565. That represented in Figure 565, *B* is the more powerful and practical arrangement. The load can be raised by the exertion of less effort since five ropes instead of four support the movable block. Fixed pulleys serve only to change the direction of the force applied.

The mechanical advantage of this block and tackle may be found from the movement of the rope. If we pull on the free end of the rope (Figure 565, A) so as to raise the load 1 foot, each of the four ropes between the fixed and movable blocks would have to shorten a foot. The total shortening of 4 feet must be taken up by the rope on which we are pulling. Our hand, then, moves downward 4 feet. That is, our effort is exerted through four times as great a distance as the load (resistance) is moved. Since the effort distance is four times the resistance, the effort need be but one fourth of the resistance in order that effort × distance may equal resistance × resistance distance. That is, the work done *by the effort* equals the work done *on the resistance.*

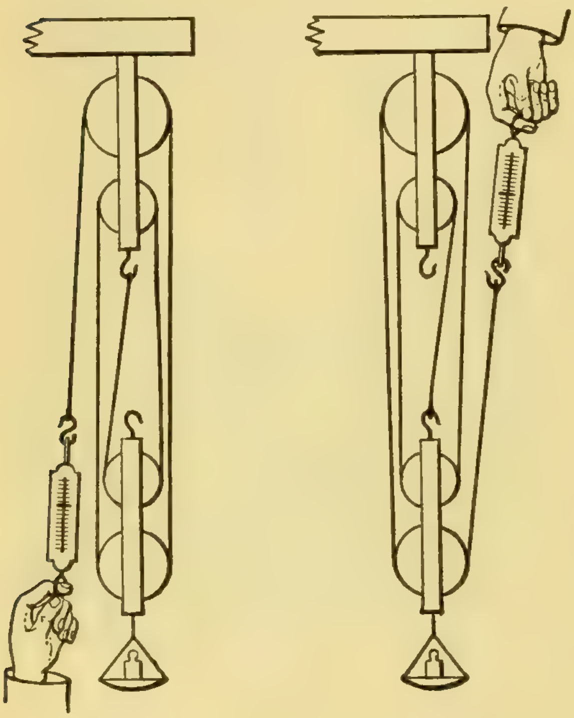


FIGURE 565. — In A, four ropes support the resistance; in B, five ropes hold up the weight. What is the mechanical advantage of each combination?

Thus, neglecting friction, a weight of 200 pounds can be raised by a pull of 50 pounds. The mechanical advantage of 4 (200 ÷ 50) is numerically the same as the number of ropes that share in the support of the load raised.

In general, the mechanical advantage of a combination of pulleys is equal to the number of ropes that pull directly on the resistance. This is known as the Law of Pulleys.

While there are many examples of simple machines in practical use, the machines of shop and factory are compound

machines. Several of the simple machines are linked in the operation of the compound one (Figure 566), each simple machine contributing its special advantage to the complex but orderly series of movements in the composite one. The locomotive, the automobile, and the many machines in our

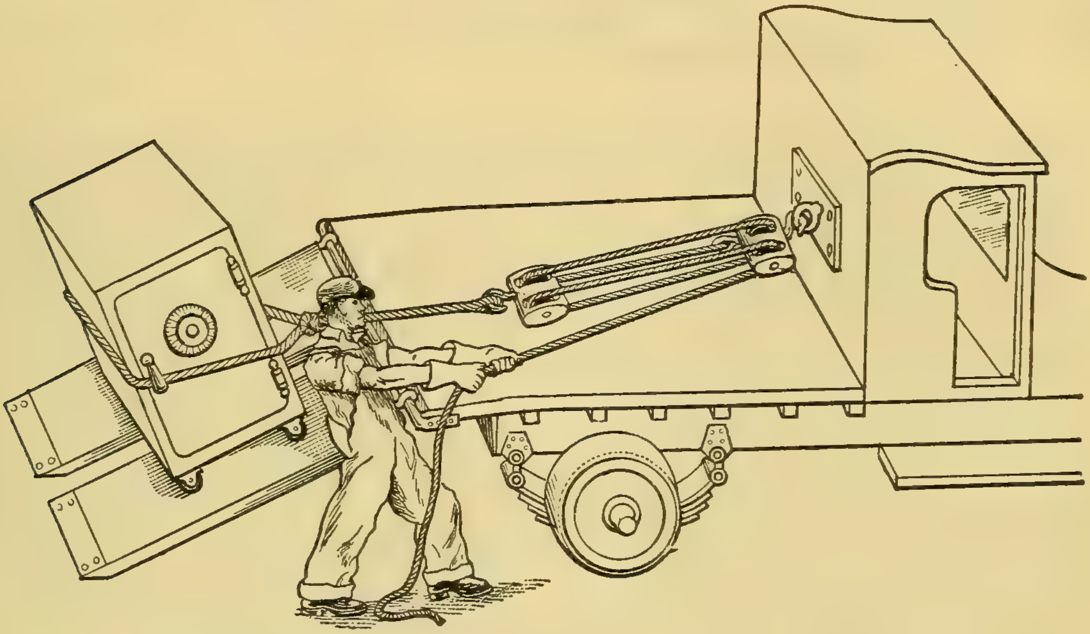


FIGURE 566.—A COMBINATION OF SIMPLE MACHINES.

The man pulls a long way with a small force to raise the heavy safe a short distance.

factories that seem almost to possess human intelligence, are good examples of composite machines.

The bewildering combination of simple machines into a compound one does not prevent us from finding the mechanical advantage of the latter. In order to find the mechanical advantage of a compound machine, it is only necessary to find the distance that the effort travels at one end of the machine and the distance that the resistance travels at the other end:

$$\text{mechanical advantage} = \frac{\text{effort distance}}{\text{resistance distance}}.$$

389. Simple Machines Used to Reduce or Magnify Motion. — The lever, the wheel and axle, and the screw are

employed in many practical devices for magnifying small motions, without any idea of mechanical advantage. Examples of such applications we have already seen in the combination of levers used in the aneroid barometer (Figure 101), the rack and pinion in the butcher's scale (Figure 11), the combination of lever and wheel and axle in the pressure gage (Figure 42). It will be seen in all of these cases that the effort is applied to the smaller part of the machine, so that the indicator (resistance) will move through the larger distance. In clockwork, the force is transmitted from pinion to wheel, so as to make the minute hand move 12 times as far as the hour hand, and the second hand farther than the minute hand.

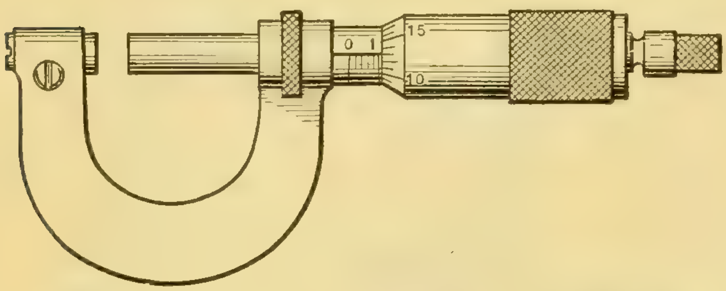


FIGURE 567. — The micrometer caliper makes use of the screw principle to secure accurate measurement of small distances.

The micrometer caliper (Figure 567) is extensively used by machinists and others to measure small distances accurately. For English measures, it is made with 40 threads to the inch. The head of the screw is made into a sleeve, the edge of which is divided into 25 divisions. For each division of the circumference of the sleeve that is moved past the index in turning the screw, the distance between the jaws of the

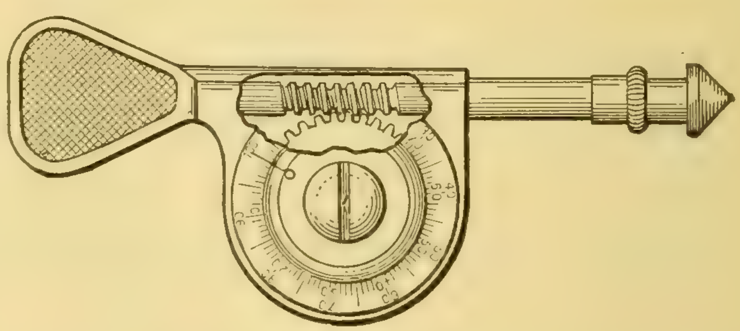
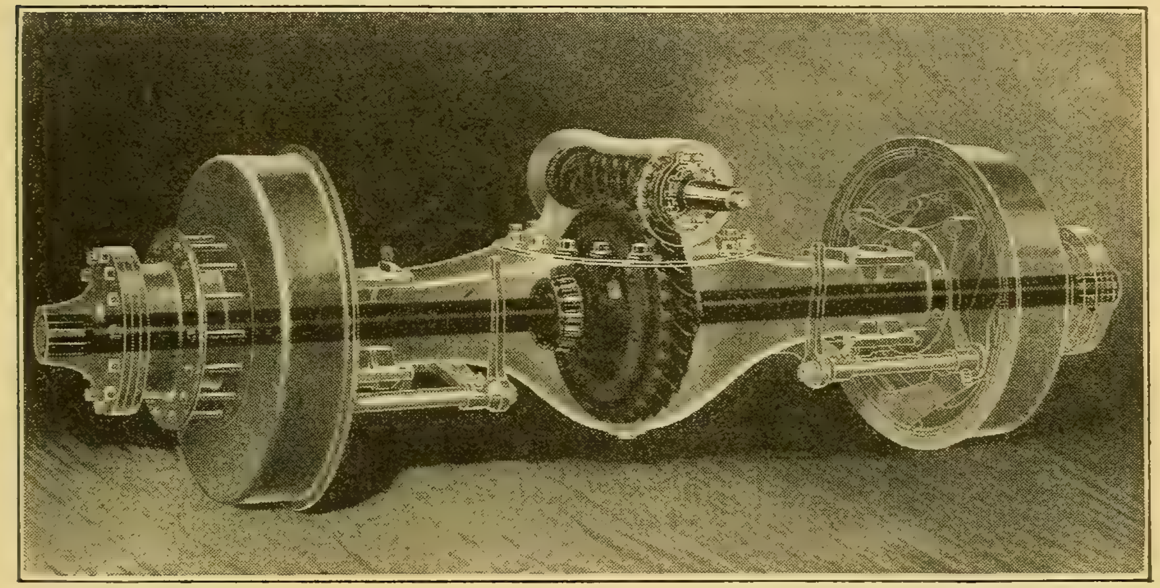


FIGURE 568. — The spindle of the revolution counter revolves 100 times in order to turn the wheel once. The turns of the wheel are slow enough to be counted.

caliper will be changed by $\frac{1}{25}$ of $\frac{1}{40}$ of an inch, that is, by $\frac{1}{1000}$ of an inch. Metric micrometers measure to $\frac{1}{100}$ of a millimeter.

In the revolution counter (Figure 568), the spindle of the counter has a spiral thread cut in it, which engages in a similar thread cut in the rim of the counter wheel. The pitch of the threads is $\frac{1}{100}$ of the circumference of the counter wheel. So



Courtesy of Timkin Detroit Axle Co.

FIGURE 569. — The worm gear on the truck gives a large mechanical advantage, because many revolutions of the engine cause only one revolution of the drive wheels. A roller bearing is seen at the left of the large gear.

the spindle, which is inserted into the center of the shaft whose speed is to be measured, makes 100 revolutions to one of the counter wheel. It is interesting to note that this same combination of pinion and worm wheel constitutes the *worm gear* (Figure 569), an exceedingly powerful machine when the effort is applied to the pinion and the wheel acts on the resistance. Worm gears are frequently used in derricks and in the driving mechanisms of many automobile trucks. The steering post of an automobile often terminates in a worm gear.

QUESTIONS

1. Define the *lever*. What is the *fulcrum?* Give three examples of the lever.

2. Write the work equation that applies to the lever in common with other simple machines.

3. A man with a force of 100 pounds lifts a heavy stone 4 inches, using a crowbar as a lever. In doing this, his hands at the top of the bar move 12 inches. Find (*a*) the work done, (*b*) the weight of the stone.

4. State the mechanical advantage of the lever in terms of its dimensions.

5. What is the mechanical advantage of the lever in Question 3?

6. Show that the wheel and axle is a modified form of the lever.

7. Give an equation that shows the application of the principle of work to the wheel and axle in terms of its dimensions.

8. What determines the mechanical advantage of a wheel and axle?

9. Make a diagram of a wheel and axle that would have a mechanical advantage of 4. What force must be applied to the wheel in order to have the rope on the axle exert a pull of 100 pounds?

10. What force will be necessary at the rim of a wheel of 2-foot radius, if the rope, exerting a resistance of 200 pounds winds on an axle 6 inches in diameter?

11. Name three practical applications of the wheel and axle, and state in each case how the effort force is applied to the wheel.

12. What is the *pitch* of a screw? How is the mechanical advantage of the screw found?

13. Describe a *fixed* pulley. Why is its mechanical advantage only 1? What is the only reason for using it?

14. Describe an experiment that demonstrates the mechanical advantage of a single movable pulley.

15. What number represents the mechanical advantage of a single movable pulley? To what is this due? What is sacrificed to gain this mechanical advantage?

16. Explain how two kinds of pulleys are used in a painter's scaffold.

17. Make a diagram of a single fixed pulley, indicating the size and location of the effort applied and of the resistance overcome. Make clear the distance one moves compared with the other.

18. Answer Question 17 for a single movable pulley.

19. Give examples of the practical uses of single fixed pulleys and of single movable pulleys.

20. Describe the construction of a commercial block and tackle, including in your description the names of the three principal parts.

21. (*a*) Describe an experiment that shows how the mechanical advantage may be determined for the combination of two fixed pulleys with two movable ones. (*b*) Explain how the number of the cords that pull on the resistance in such a combination determines its mechanical advantage.

22. State the *Law of Pulleys*.

23. Three movable and three fixed pulleys are combined in a block and tackle. With the aid of a diagram, determine the mechanical advantage. What weight will be lifted by a pull of 50 pounds? When the weight is lifted 8 feet what will be the effort distance? Why?

390. Friction. — Children run and slide on icy surfaces, but some unseen force soon stops their motion. In order to continue this motion the child equips himself with skates, thereby reducing the force that stops him. More sedate pedestrians, to decrease slipping, wear rubber-soled footwear and thus increase the force that keeps them from ungraceful attitudes. In the summer, when icy walks are not available for sliding places, the boy fastens wheels upon his feet and reduces the force that robs him of his easy forward motion. The resistance hindering the motion of one body over another is *friction*. Friction is at once a necessity and a nuisance. Walking is possible only because of the friction between shoe and sidewalk. Automobiles and trains move because of friction between drive wheels and pavement or rails. Both movements are stopped by the friction of brakes or road. On the other hand, friction between solid surfaces or between solids and fluids reduces all motions and requires a constant expenditure of energy to overcome it.

Friction is partly due to the interlocking of projections on

the surfaces in contact (Figure 570), and it is partly due to the deformation of the contact surfaces by the pressure of one body on the other. When steel is rubbed on steel, the projections of one surface probably slip into spaces between projections in the other. The motion between the surfaces is kept up only by continually shoving one set of projections out of the depressions in the other surface. That something of this sort occurs is shown by the fact that rubbing surfaces in machinery are made of unlike metals wherever possible. In this way there is less chance of fitting one set of projections into the different size spaces of the other surface. Babbitt metal or brass is commonly used as bearing surfaces for steel shafts. Moreover, friction is always greater at the beginning of motion than between rapidly moving surfaces, probably because there is less chance for projections to interlock when in motion.

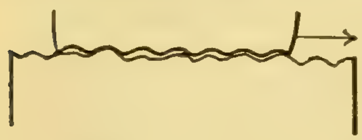


FIGURE 570.—Sliding friction is caused by the interlocking of tiny projections on the contact surfaces.

When one body is moved over another, both surfaces are likely to be deformed either permanently or temporarily. In soft earth, a wheel or sledge will cut a deep groove and this cutting makes forward motion difficult. An automobile tire on the pavement is noticeably flattened as each part of the wheel in turn touches the street. Continual flattening and the deformation of the roadway retard motion (Figure 571) and hence come under the definition of friction. As in other

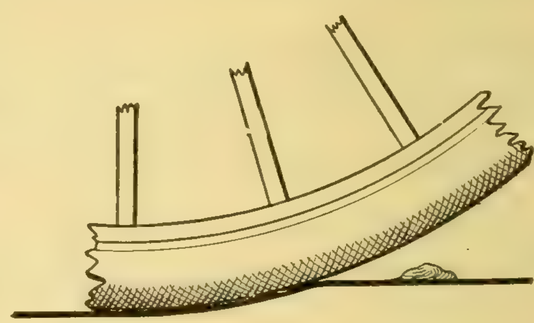


FIGURE 571. — Wheels and roadways are slightly deformed as the wheel moves over the road. Small obstructions cause the wheel to be lifted as it strikes them. The deformation and the lifting retard the motion.

cases, the work done in overcoming friction causes heat, which in the case of the automobile tire sometimes causes a blowout.

391. Sliding and Rolling Friction.—Mankind early learned to distinguish between two kinds of friction: *sliding friction and rolling friction.* As it was discovered that a round body could be rolled much easier than it could be dragged along

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FIGURE 572. — Compare the power of the engine and the weight moved against sliding friction with the power and the weight moved against rolling friction in Figure 573.

(Figure 572), the sledge was replaced by a rude cart. The cart in turn gave way to a better made wagon with fitted, oiled axles in metal hubs (Figure 573); and these in our day to the same axle with ball or roller bearings

With the same surfaces in contact, sliding friction is commonly much greater than rolling friction. In sliding friction, the surface irregularities are constantly bumped into each other and worn away. In rolling friction, however, the small elevations are lifted out of the indentations with correspondingly less wear and less effort.

392. Increasing and Decreasing Friction. — We sprinkle ashes or sand on icy sidewalks to increase the friction between the surface and our shoes. The engineer or motorman sands the track to obtain more friction, so that his drive wheels will not slip in starting. In tractors (Figure 574) large, rough treads are used to increase friction. Belts on machines are resined to prevent slipping, and the violinist does the same

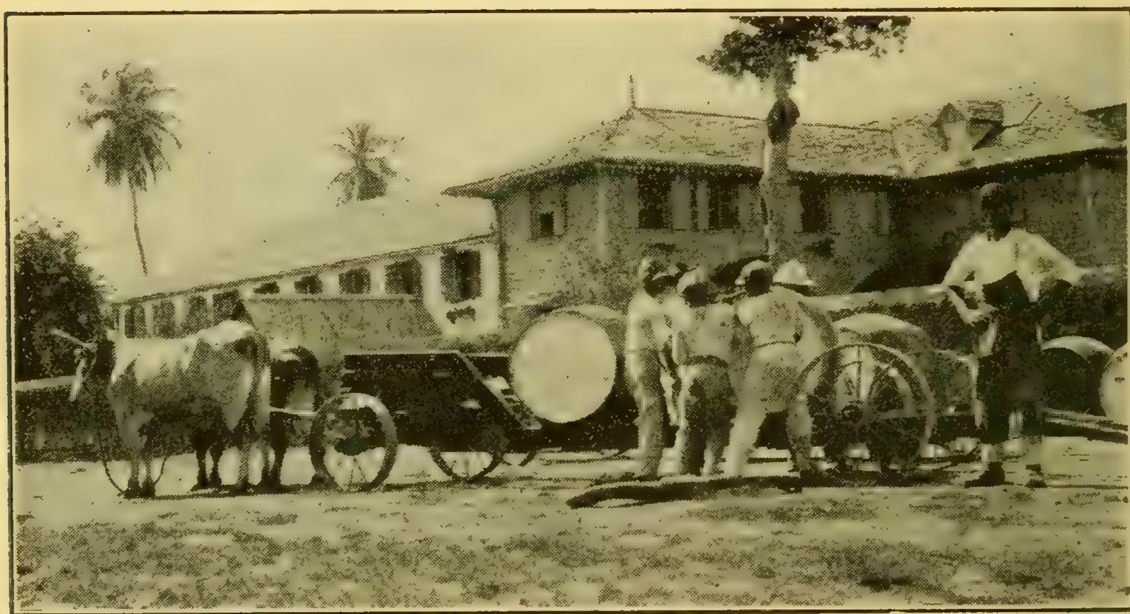

FIGURE 573. — A small force moves a large load in this picture because rolling friction is the only resistance to be overcome on level ground.

thing to his bow to increase the friction between it and the string. Rubber is much used for a variety of purposes, because it moves with difficulty over most surfaces.

To decrease friction, the first resort is to substitute rolling for sliding friction. Every wheeled vehicle is the outcome of this change, and the sliding friction is done away with except where the axle slides in the hub or journal at one point in its rotation. Ball or roller bearings, however, bring about an almost complete substitution of rolling for sliding friction, thus accounting for their use in bicycles, automobiles, sewing machines, lawnmowers, and many other machines. Even in

heavy machinery, roller bearings (Figure 569) are widely used for shafts, so as to get rolling friction.

The second method for reducing friction is to make the rubbing surfaces as smooth as possible. The great development of the bicycle and the automobile showed the necessity for reducing friction to a minimum, and the common standard of accuracy in the adjustment of contact surfaces is 0.001 inch. Hard surfaces once made smooth do not wear rough. Watchmakers therefore use small jewels harder than steel as bearings for their watch movements. The number of these jeweled bearings is to some extent an index to the value of the watch.

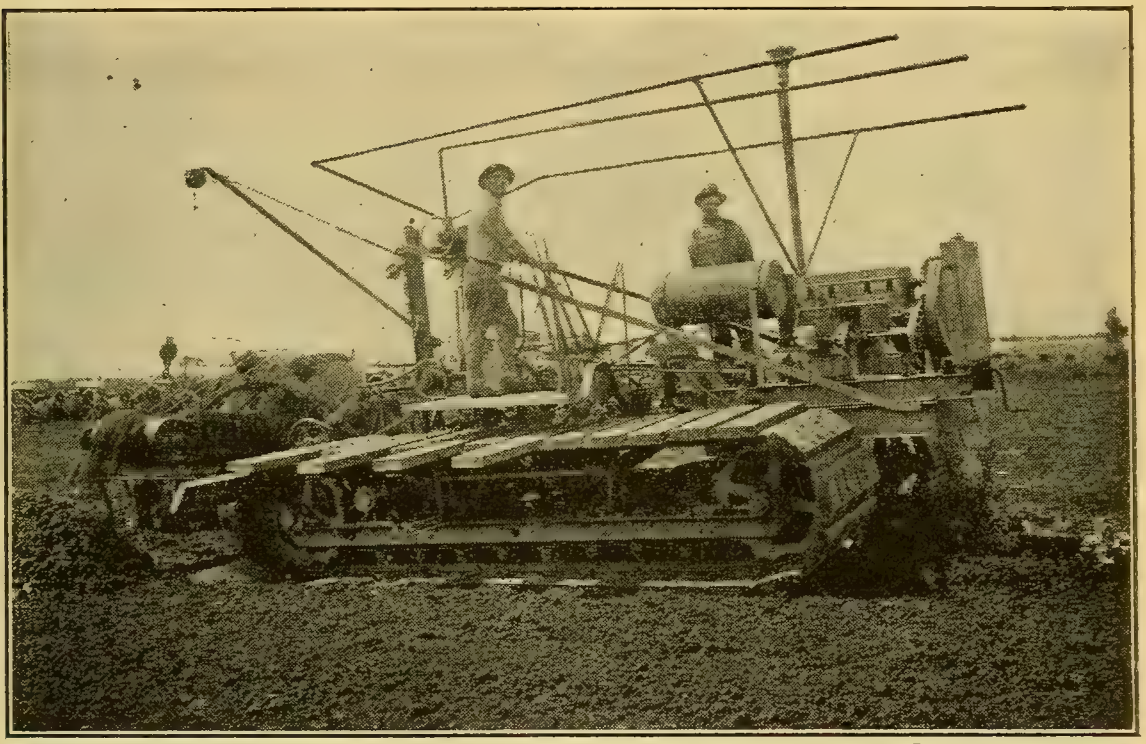

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FIGURE 574. — A large friction force is needed between the ditching machine and the ground in order to drive the machine. The caterpillar tread provides the necessary friction.

Finally, after substituting rolling for sliding friction and smoothing the surfaces as much as possible, the contact surfaces are lubricated. Lubrication consists of placing

some substance, such as oil, grease, or graphite, between the contact surfaces. The substances spread out in a thin film, and thus prevent actual contact between the two surfaces that would otherwise rub against each other.

393. Coefficient of Friction. — The more we press the palm of the hand down on a table, the harder it is to slide the hand on the table. Increasing the pressure increases the sliding friction. An expressman loading trunks on his truck increases the friction on the axles since the added weight means more pressure. *The ratio of friction to the pressure causing it is the coefficient of friction.*

The coefficient of friction has different values according to the kinds of surface in contact. It is greater between rubber soles and a polished floor than between leather soles and the same floor. Under similar conditions, the coefficient of friction between two given materials is a constant quantity.

394. Efficiency. — In every machine a certain amount of energy must be supplied to overcome friction. This amount of energy causes the energy input to exceed the output by a certain percentage, depending upon the smoothness with which the machine runs. The energy used to overcome friction reappears as heat generated at the rubbing surfaces. This heat is dissipated uselessly into the air. In every machine, therefore:

the energy expended = useful energy delivered + heat.

The *efficiency of a machine* is the ratio of useful work accomplished to the energy expended on the machine to cause it to perform this work, or briefly:

$$\textbf{efficiency} = \frac{\textbf{useful output}}{\textbf{input}}.$$

Efficiency is always expressed in a per cent; it must always be less than 100%, since the overcoming of friction and some other internal losses always makes the output smaller than the input.

The efficiency of a simple machine like the inclined plane can readily be shown by an experiment.

EXPERIMENT 146. — Select a smooth board about 4 feet long, and fasten it so that one end is 1 foot higher than the other (Figure 575).

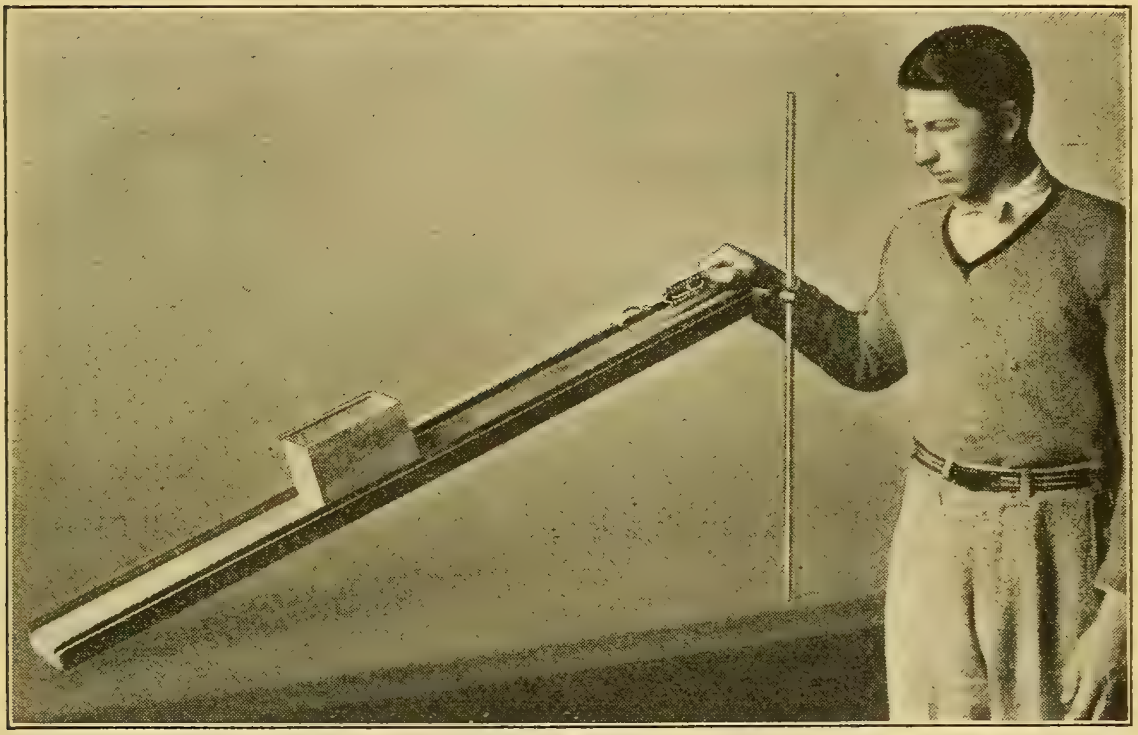

FIGURE 575. — Friction causes the boy to do more work dragging the box up the plane than he would do in lifting it directly.

Put weights in a chalk-box until the box and its contents weigh 5 pounds. Then draw the box at uniform speed up the board by means of a cord attached to a spring balance and read the balance during the motion.

Find the work actually done in pulling the box up the plane by multiplying the length of the board by the pull on the balance. *Result?* Find the useful accomplishment by multiplying the height of the raised end by the weight lifted. *Result?*

Which quantity of work is greater? What makes the difference? Express the ratio of useful work to the expended work as a per cent. What does the per cent represent?

Energy is wasted in the pulley in overcoming the friction at the pulley bearings, in overcoming the stiffness of ropes, and in lifting the movable pulley itself. Friction of ropes and bearings reduces the efficiency of the wheel and axle. Friction makes necessary a greater expenditure of energy in moving a box up an inclined plane. Levers have but little friction to overcome, but often the weight of the lever bar itself requires the expenditure of energy without useful return. In these simple machines, as in more complex ones, the lower the efficiency, the greater must be the force to overcome a given resistance, or the less will be the resistance overcome by a given force.

The use of a machine, as for example the pulley, allows a workman to move bricks to the top of a building under construction without the necessity of climbing ladders to carry the brick. If he does carry the brick up the ladders, he does more useless work in hoisting his own weight than he does useful work in lifting the brick. The bricklayer may also do much useless work in lifting part of himself, if he has to stoop over to pick up each brick before he lays it. The attempt of certain men to eliminate this useless work in all branches of industry has made the word *efficiency* a well-known term.

395. Efficiency of Some Common Machines. — The steam locomotive is probably the most wasteful common machine, since it accomplishes about 6% of the work which should be obtained from the coal that it consumes. Stationary steam engines frequently have a condenser, which increases the efficiency to 10%. Gasoline engines average a little higher, but vary somewhat according to their condition. Electrical machinery of all kinds has a relatively high efficiency, the per cents ranging from 80% in large motors to 99% in transformers.

The energy losses in all machines eventually are dissipated as heat. While the total amount of energy in the universe remains the same, the available energy is constantly decreasing on the earth. At present we are using up the stored energy of previous ages. When our supplies of coal and oil are gone, we shall be dependent on the energy received from day to day from the sun. This energy is now largely wasted, except as the precipitation of evaporated water is made to furnish water power at a few places.

QUESTIONS

1. Why do we not get out of a simple machine all the work we put into it?

2. Define *friction*. Explain how surface irregularities cause it.

3. Distinguish between *sliding friction* and *rolling friction*. Give an example of each kind.

4. Compare sliding friction and rolling friction with respect to the action of the elevations and depressions of surfaces in contact.

5. Why is it difficult to walk with new leather soles on a polished floor?

6. Give three instances in which it is desirable to increase friction.

7. Why is rolling friction substituted for sliding friction? State how this is done in vehicles and in some common household machines.

8. What is a second general method for decreasing friction. How is this applied to watches? Give another application of this method.

9. Define *coefficient of friction*.

10. Why is part of the energy applied to a machine lost? What becomes of it?

11. Distinguish between rolling and sliding friction. State three cases in which sliding friction can be advantageously replaced by rolling friction.

12. In what ways may friction be lessened? What substances are used to increase friction between contact surfaces?

13. What becomes of the energy used in overcoming friction? Give an example.

14. Define the *efficiency of a machine*. Give an equation for it.

15. How does the friction within a machine affect the efficiency of the machine? Name instruments or machines in which you think this loss may be important. Name others where this loss would be negligible.

16. Describe an experiment that shows how the efficiency of an inclined plane can be found.

17. How great a force is required to *hold* a weight of 250 lbs on an inclined plane 10 ft long and 4 ft high? If 125 lbs are required to *move* the load up the plane, what is the efficiency of the plane?

18. A man applies a force of 60 lbs in rolling a desk weighing 180 lbs up a 10-foot skid into a doorway 3 ft above the sidewalk level. What is the efficiency of this inclined plane?

19. A system of pulleys has the movable block supported by 5 ropes (strands). How much force is necessary to hold a 500-pound weight stationary? If the efficiency of the system is 80%, what effort will be required to raise the weight?

20. A force of 200 lbs moves 5 ft when applied to a block and tackle so as to lift a piano weighing 500 lbs up 1 ft. What is the efficiency of the block and tackle?

21. State how energy is wasted in some of the simple machines.

22. How does the efficiency of a machine affect the amount of useful work done by it? What becomes of the useless work?

23. Compare the efficiency of some of the common engines.

SUMMARY

Work is done when motion or displacement is produced by a force.

Work is measured by the product of the force (F) and the distance (d) through which the force is exerted; that is, **Work** $= Fd$.

Units for measuring work are the foot-pound and the gram-centimeter.

A foot-pound is the amount of work done when a pound force acts through a distance of one foot.

A gram-centimeter is the amount of work done when a gram force acts through a distance of one centimeter.

A machine is a device by which useful work is done in such a

way that there is a gain to the user in effort, speed, or convenience. Among the simple machines in which there is a single transfer of energy, there are the inclined plane, the wedge, the screw, the lever, the wheel and axle, and the pulley. These are elements used in building complex machines.

An inclined plane enables work to be done with less effort. The smaller the effort force used to do a given amount of work, the greater must be the distance through which the effort acts.

The law of the inclined plane is:

$$\frac{\textbf{resistance}}{\textbf{effort}} = \frac{\textbf{length of plane}}{\textbf{height of plane}}$$

This equation is useful in finding the value of one of the quantities when the value of the other three are known.

The wedge in its simplest form is a movable inclined plane. In general, the sharper the angle of the wedge, the less the effort required to make it overcome a given resistance.

More work cannot be done by a machine than is expended on it. This idea expressed by the **Law of Work** is:

$$\textbf{work input} = \textbf{work output.}$$

This equality is strictly true only for the ideal machine in which there would be no friction.

The mechanical advantage of a perfect machine is the number obtained by dividing the resistance by the effort:

$$\textbf{mechanical advantage} = \frac{\textbf{resistance}}{\textbf{effort}}.$$

The lever is a rigid bar free to move about a fixed point called the fulcrum. In the lever:

$$\frac{\textbf{length of effort arm}}{\textbf{length of resistance arm}} = \textbf{mechanical advantage.}$$

The wheel and axle is a modified form of the lever in which the effort is applied to the circumference of the wheel which turns the axle. With this machine:

$$\textbf{mechanical advantage} = \frac{\textbf{radius (or diameter) (or circumference) of wheel}}{\textbf{radius (or diameter) (or circumference) of axle}}$$

The screw consists of a cylinder, around which runs a thread that fits into a corresponding groove in a fixed base. The **pitch** is the vertical distance between two successive threads. The screw is usually turned by a bar that fits into the cylinder.

The mechanical advantage of the screw is the ratio of the circumference described by the bar to the pitch of the screw.

The pulley is employed as a fixed pulley, as a movable pulley, and as various combinations of the two kinds.

The mechanical advantage of a **fixed** pulley is 1. Its only real gain is a change in direction. The mechanical advantage of **a single movable** pulley is 2. Although the effort is but half the resistance, the gain is accomplished at the sacrifice of making the effort move through twice the distance.

Blocks and tackles are combinations of fixed pulleys with movable pulleys. In general, the **mechanical advantage** of a combination of pulleys is equal to the **number of ropes** that pull directly on the resistance (Law of Pulleys).

Friction is the resistance that hinders the motion of one body over another. It is due to the irregularities in the surfaces that are in contact, and to the deformation of the contact surfaces by pressure. Friction makes the work put into a machine greater than the **useful** work accomplished by it.

In **sliding** friction, the contact surfaces of the two bodies slide over each other; while in **rolling** friction the contact surfaces roll on each other. It is sometimes desirable to increase friction, as in the sanding of sidewalks and railroad tracks, and in applying preparations to belts on machinery to prevent slipping.

Friction is decreased by (1) substituting rolling for sliding friction, (2) making the rubbing surfaces as smooth as possible, and (3) lubricating the surfaces.

The coefficient of friction is the ratio of the friction to the pressure causing it.

In every machine, the energy expended equals the useful energy expended plus heat.

$$\textbf{efficiency of a machine} = \frac{\textbf{useful output}}{\textbf{input}}.$$

Efficiency in machines is always expressed by a **per cent.** Friction is the chief cause of the loss of efficiency in most machines.

EXERCISES

1. What is a simple machine? Name five of them.

2. What two advantages may we get by using simple machines? Do they save us work?

3. Name the simple machine that is found in each of the following: door knob, a painter's scaffold, a grindstone, a meat cleaver, an oar, a bread mixer, a winding hill road, a coffee grinder, and a screw driver.

4. How can we find the mechanical advantage of a small inclined plane by means of a ruler?

5. Would the mechanical advantage of an inclined plane be increased when (*a*) the effort force was increased, (*b*) the pitch of the plane was increased? Explain.

6. A mass of 200 lbs is being moved. Will the force be greater or less than 200 lbs when (*a*) the weight is being pulled along a horizontal board, (*b*) the weight is being pulled up a 20 % slope?

7. Make a diagram of a seesaw with a 120-pound boy sitting on one end of the 10-foot plank and an 80-pound boy on the other end, and indicate the position of the fulcrum.

8. Which hand does the more work in sweeping a rug with a broom? Explain.

9. The radius of the front sprocket wheel of a bicycle is 4 in and the length of the pedal crank 7 in. What kind of a machine is illustrated? How much resistance on the chain may be overcome by a 40-pound push on the pedal?

10. Draw a wheel and axle showing dimensions that will give a mechanical advantage of 5. Change the dimensions so as to get a machine with a mechanical advantage of 10.

11. Could a brake be applied more effectively to the circumference or to the axle of a rotating wheel? Why? Which method is used in the modern bicycle?

12. Using a jackscrew (Figure 558) having 5 threads to the inch, what weight will be raised by a force of 10 lbs applied by a bar moving through a 10-foot circumference?

13. In a bicycle, the driving force on the rear sprocket with 2-inch radius overcomes a resistance on the rear tire 15 in from the center. How much resistance can be overcome at the road by a 150-pound force at the rear sprocket? Is speed lost or gained by this combination?

14. How is the mechanical advantage of a system of pulleys determined by inspection? Draw a system of pulleys whose mechanical advantage is 5, indicating a suitable resistance and effort. Show how far the effort must move when the resistance is lifted 10 ft.

15. Make a diagram of a set of pulleys by which a 100-pound effort will sustain a resistance of 600 lbs.

16. State the law of work that applies to machines. Illustrate by a simple problem based on a pulley system.

17. Make a labeled drawing of (*a*) an inclined plane, (*b*) a wheel and axle, and (*c*) a pulley system. For each machine give the necessary dimensions, etc., so that a force of 40 lbs may sustain a weight of 200 lbs in each case.

18. A force of 1800 lbs is required to draw a 4000-pound safe up an incline of boards 10 ft in length into the floor of a truck 4 ft from the ground. What is the efficiency of the plane?

19. An effort of 30 lbs applied through 50 ft on a wheel and axle raises a weight of 60 lbs through a distance of 20 ft. What is the efficiency?

20. On a crane, the rope is wound upon an axle of 4 in diameter. The crank attached to the axle is 14 in long. When an effort of 100 lbs is applied at the crank, it produces a pull upon the rope of 650 lbs. Find the efficiency of the combination.

21. A system of movable pulleys has the movable block supported by 10 ropes. How much effort should be applied to hold a 500-pound weight stationary? If the efficiency of the system is 80%, what effort will be required to raise the weight?

22. The pilot of a ferry boat applies a force of 20 lbs to the steering wheel which has a radius of 30 in. The rope from the rudder is wound upon an axle of 3-inch radius. If there is a pull of 190 lbs upon the rudder rope, what amount of the pull overcomes friction?

CHAPTER XXIX

ENERGY AND POWER

WORK is done when physical changes are accomplished against opposition. A lifted stone (Figure 576), a moving hammer, the compressed gas in an automobile cylinder, a stick of dynamite, or the human body are all able to bring about physical changes against opposition and are thus able to do work. *The capacity for doing work is energy.* Scientists have reduced the fundamentals of physics to just two realities: *energy* and *matter.* When we are discussing energy, we should keep in mind that it is the foundation idea of physical knowledge. Matter is considered as the means by which energy is transformed.

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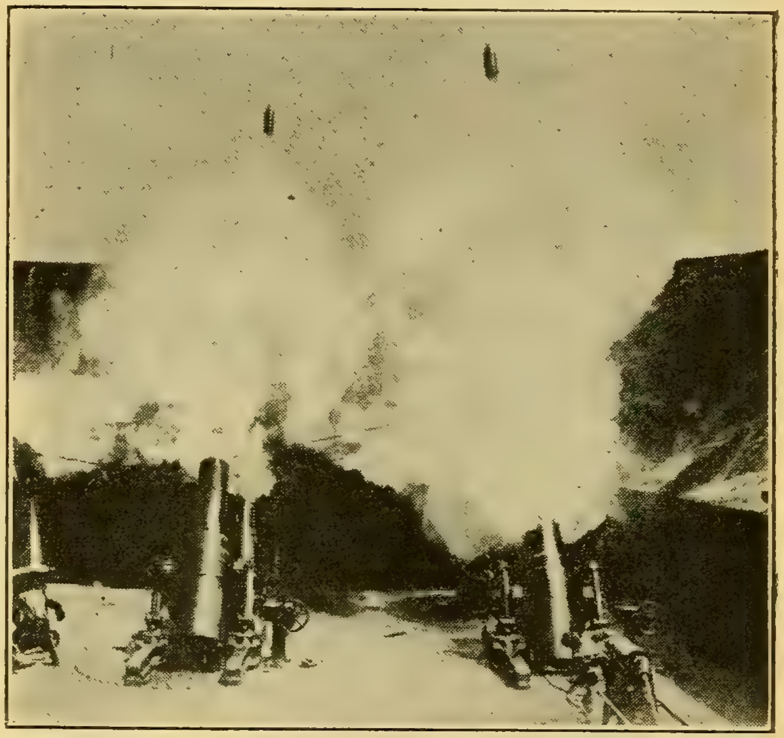
FIGURE 576. — Ages ago, work was done to raise this huge stone to its present position. Now it possesses energy because of the work done upon it.

396. Kinds of Energy. — In examining the examples of energy in the previous paragraph, we find that there is a

difference in the kind of capacity for doing work. The hammer can do work on a nail because the hammer is moving. The gas can likewise do work on the piston because the molecules of the gas are moving rapidly. Every moving body can do work because of its motion, and this energy is known as *kinetic energy* (Figure 577).



Courtesy U. S. Army Information Service.

FIGURE 577. — JUST AFTER FIRING.

The kinetic energy of the exploding powder has started the projectiles in flight and caused the guns to recoil.

The lifted stone or weight has energy because of its position. Work has been done on it to lift it, and for some unknown reason which we name gravity, it tends to fall back to the earth. If allowed to fall, it acquires velocity and is therefore able to do work because of its kinetic energy (Figure 578). Its energy resulting from its separation from the earth is *potential*. Dynamite and the human body both possess potential energy because of chemical action that has taken place in their formation. A bent bow and a compressed spring have potential energy stored in them because of the displacement of the molecules while under strain.

397. Conservation of Energy. — In an automobile engine, when gasoline is burned its energy disappears and the

gasoline is no longer able to do work. The gasoline itself no longer exists as gasoline but as parts of the exhaust gases. However, the energy of the gasoline is not destroyed but, in the form of heat, is still able to do work (Figure 579). About a century ago, scientists began to form an opinion that the energy in the universe, like the matter in the universe, could neither be increased nor diminished. This opinion has now the authority of a law of science and every scientist regards this law of conservation of energy as the fundamental and invariable rule for all transfers of energy. Briefly the Law of Conservation of Energy states that: *Energy can neither be created nor destroyed, but may be transformed from one kind to another without loss.*

Courtesy Popular Science Monthly.

FIGURE 578. — TESTING AUTOMOBILE AXLES.

The falling weight has kinetic energy because of its mass and velocity.

Credit for the discovery of this great principle is well divided. Mayer undoubtedly had it in mind, but lacked the clearness and perhaps the authority to have his name attached to it. Its formal statement is generally credited to Helmholtz and the experimental work that established it was done largely by Joule. As a result of experiments covering a period of years, Joule was able to show that each disappearance of energy was accompanied by the accumulation of an equivalent amount of energy in a different form.

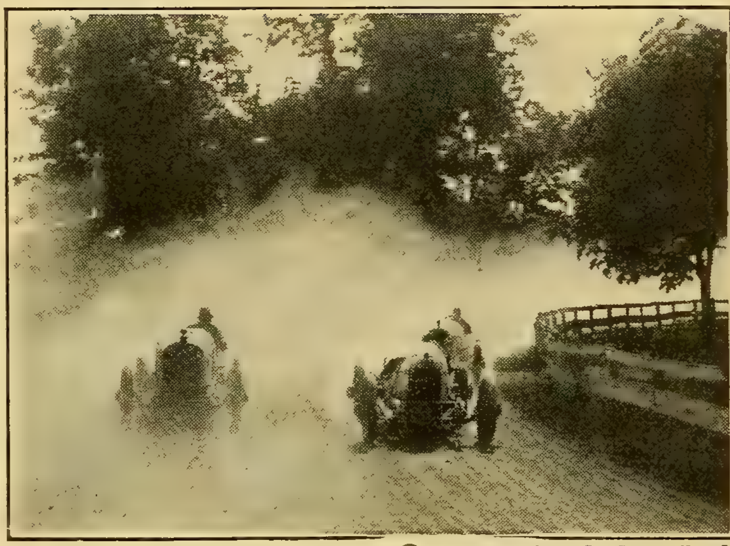


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FIGURE 579. — The potential energy of gasoline is transformed into the kinetic energy of the racing automobiles.

398. Kinetic Energy. — If a slowly moving automobile collides with a telegraph pole, it may do no more work than simply to bend the fender. A swiftly moving car has been known to break off a thick pole with which it has collided. Evidently the capacity of the moving car for doing work depends upon the *velocity* of the car. A stone striking the pole with the same velocity as the car would probably dent the wood a little. The kinetic energy of bodies must therefore depend also upon the *mass* of the moving body. In the previous paragraph, it was shown that as one kind of energy is utilized, another form of energy appears in its place. Energy is required to do the work of setting a body in motion, therefore in the moving body there appears an amount of kinetic energy equal to that used in producing the motion. The

heavier the body and the greater the velocity given to it, the more energy is required to produce the motion and the more kinetic energy is accumulated in the moving body.

Two equations we derived in Chapter XXVI give us the value of kinetic energy when the mass and the velocity of the moving body are known. From § 338 we obtain: $v = at$, where v is the final velocity of an accelerated body; also $v = \frac{2s}{t}$. Multiplying these two equations, we obtain: $v^2 = 2as$. Multiplying this equation by $\frac{m}{2}$ gives:
$\frac{1}{2}mv^2 = mas$. From § 345 we obtain: $F = ma$.
Putting F for ma in the last equation, we have:
$\frac{1}{2}mv^2 = Fs$.

But Fs is force $\times$ distance, or the work done in setting the body moving and therefore the kinetic energy of the body due to its motion.

The value of kinetic energy in terms of mass and velocity is: $KE = \frac{1}{2}mv^2$. If the units are in the foot-pound-second system, kinetic energy will be expressed in *foot-poundals,* convertible to foot-pounds by dividing by 32. In the centimeter-gram-second units, the value will be in *ergs,* convertible into gram-centimeters by dividing by 980.

Suppose it is desired to find the kinetic energy of a 5-pound brick moving 64 ft/sec. Using the equation above, we have $KE = \frac{5 \times 64^2}{2} =$ 10240-foot-poundals, or $\frac{10240}{32} = 320$ foot-pounds. It may be determined from the equations for falling bodies that a body falling from a height of 64 ft obtains a velocity of 64 ft/sec. To raise the brick to a height of 64 ft requires the expenditure of $5 \times 64 = 320$

foot-pounds of work, just the amount of kinetic energy possessed by the brick when it strikes the earth (Figure 580).

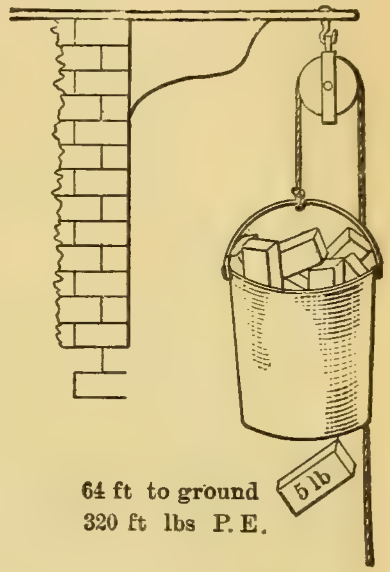

FIGURE 580. — The brick at its height has 320 foot-pounds of potential energy. In falling to the earth it will acquire velocity enough to give it the same kinetic energy.

399. Potential Energy. — Potential energy is by its nature less easy to recognize than kinetic. A spring under compression or under tension (Figure 581), may resemble another spring unstressed, but the stressed spring possesses ability to do work, as in running a clock or phonograph, while the unstressed spring has no potential energy. A black powder could be made to look like gunpowder and still be inert. Because of the arrangement of the atoms, the gunpowder is able to do a great amount of work when the atoms recombine during explosion. A Leyden

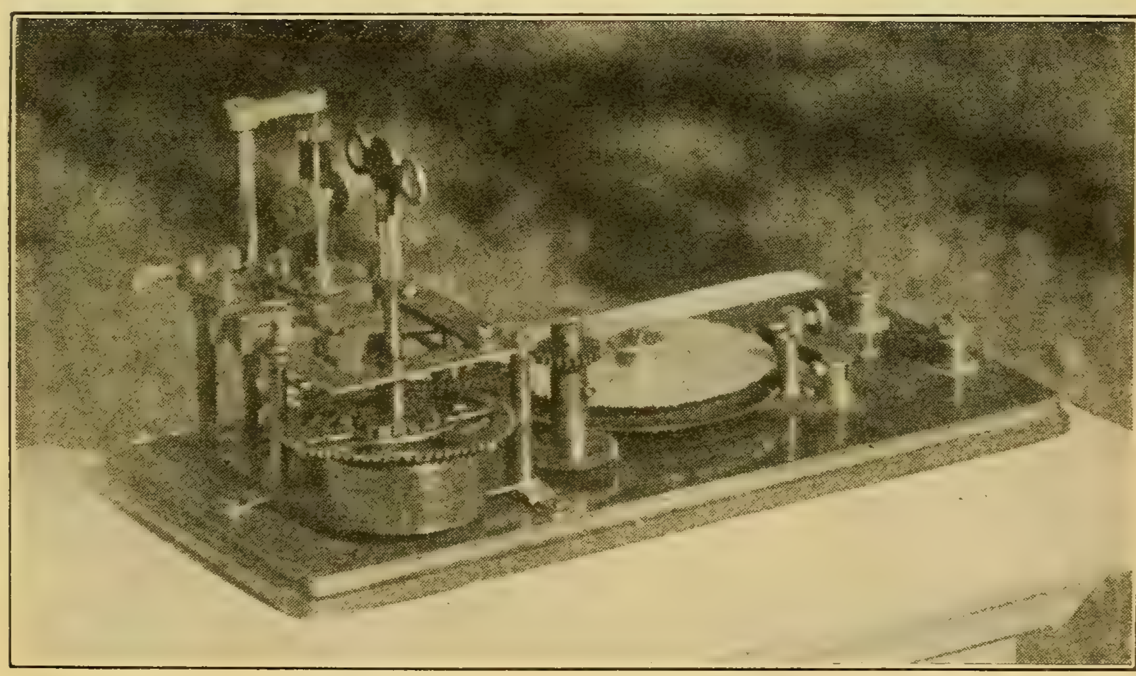

FIGURE 581. — A SPRING MOTOR.
Winding the spring stores potential energy in it. It is thus able to run the mechanism.

jar looks the same whether charged or uncharged. In one case it has no potential energy, because the electrons on the inside and on the outside of the jar are in equilibrium. The charged jar has too many electrons on one surface of the jar and too few on the other. The two sides therefore make a potential energy system, which can do work when the jar is discharged.

A stone on the ground has no potential energy with the earth on which it rests. If work is done on the stone to lift it, the potential energy stored in the stone is equal to the work expended in lifting it. When the stone is above the earth, the earth and the stone make a potential energy system by reason of their separation. In this case the potential energy is measurable, being the weight × height lifted (Figure 582). In all cases the potential energy is equal to the work done in causing the body to have potential energy, but this work is not always so easily measured.

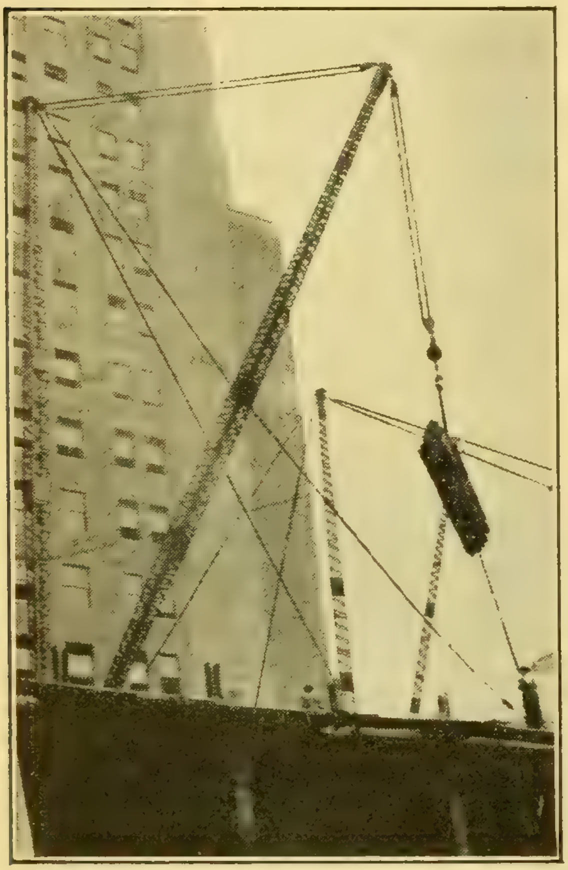

FIGURE 582. — The potential energy of the load equals the product of its weight × the height lifted.

Potential energy is always a form of energy resulting from a displacement of parts which tend to return to a former condition. This displacement is usually a separation.

400. Sources of Energy. — The deposits of coal and of oil (Figure 583) in the earth constitute our greatest supply

of potential energy because the atoms of these substances can combine with the oxygen of the air but have not yet done so. Radiant energy from the sun evaporates water from ocean surfaces and the wind blows this vapor over the land, where it falls as rain or snow (Figure 584). Falling on elevated regions, this water seeks to reach the ocean level. Work may be done by this water as it falls from natural or artificial dams (Figure 585). This separation of the water vapor and

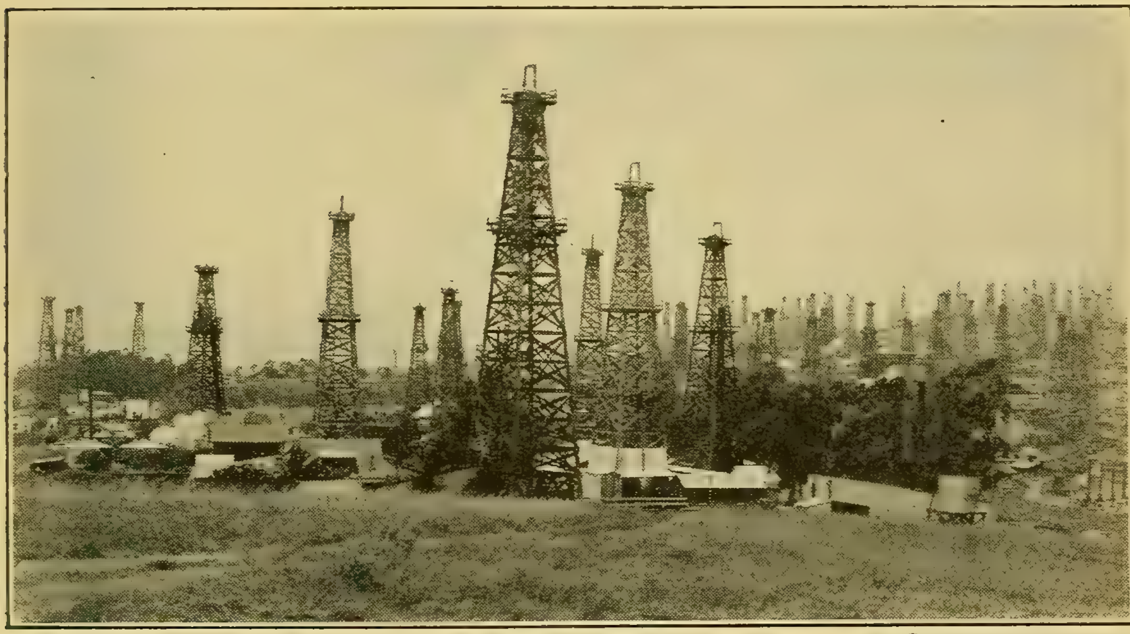

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FIGURE 583. — AN OIL FIELD NEAR SAN DIEGO.

The forest of derricks shows the extent of the reservoir of stored energy in the form of fuel.

the earth makes a vast energy reservoir, which has been in general neglected for the more convenient fuel energy of the coal. The sun is also the source of the energy by which plant life develops, and the potential energy of plant life is the source of all the energy of animal life. Going back one step farther we see that the coal and the oil deposits are simply the accumulated energy of vegetation which stored the sun's energy ages ago. *Directly or indirectly, the sun is the source of all of our present-day supply of usable energy.*

In this connection, it is of interest and importance to note two facts: The first of these is that less than a two-billionth of the sun's energy reaches the earth, and of this only a tiny fraction is caught in available form by plant life or otherwise. The second fact is that we are now drawing heavily upon energy stored in previous ages and the end of these available resources is not far off. In the immediate future we must discover a new supply of energy of which we know nothing at present, or else learn to conserve what we have.

(C) Ewing Galloway.

FIGURE 584. — A WESTERN CLOUDBURST.

Rain falling upon elevated regions constitutes an important source of potential energy. How is the sun's energy involved?

401. Energy Conversions. — A swinging pendulum moves faster as it approaches the middle of its arc, and then, as it rises on the other side, it loses velocity as it gains height (Figure 586). As it moves upward, it is changing its kinetic energy of motion to the potential energy of elevation. When it reaches its highest point of swing, its velocity and hence its kinetic energy is zero, but its potential energy is at a maximum. Falling again, its potential energy becomes kinetic, until at the lowest point of the arc its velocity and therefore its

kinetic energy are at a maximum while its available potential energy is zero. A stone thrown vertically into the air illustrates the same change of one of these energies into the other.

These are two simple cases of the conversion of energy from one kind to another. In more complicated ways these

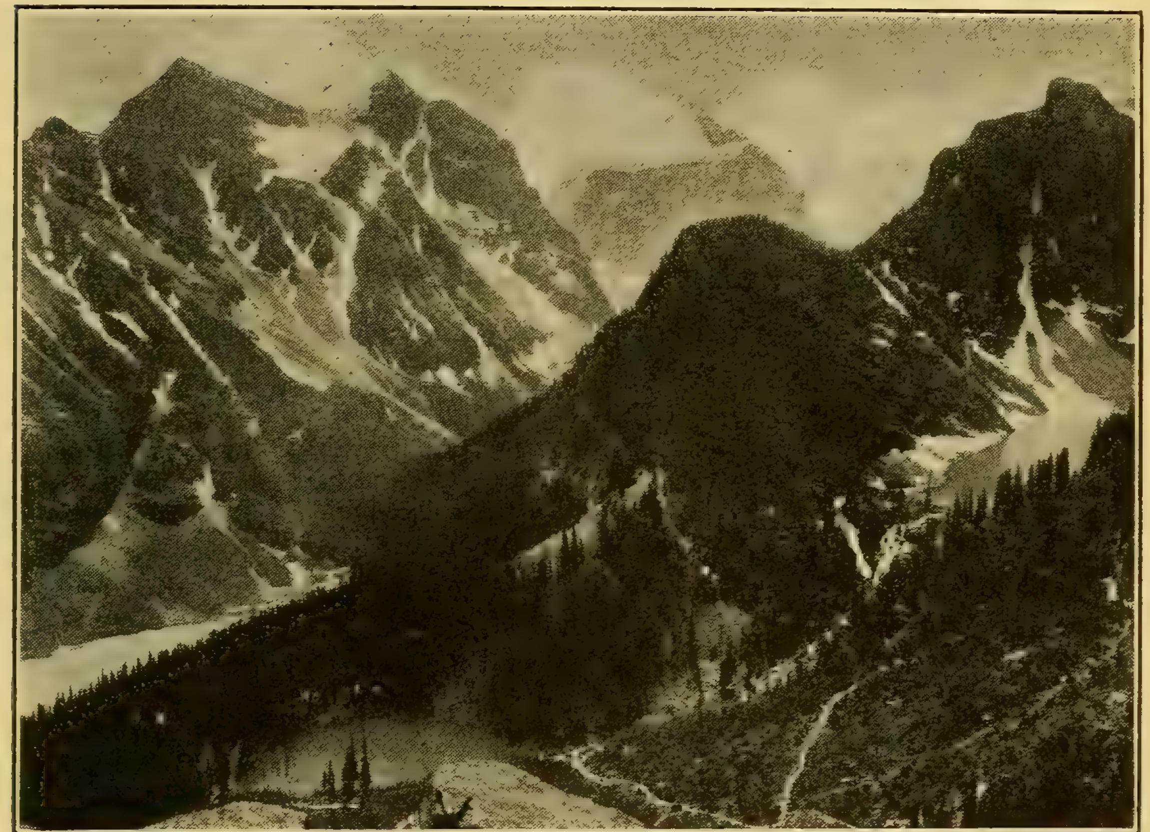

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FIGURE 585. — LAKES IN THE CANADIAN ROCKIES.

Water is stored in these mountain lakes at three different levels; for each foot of fall from one level to the next, each pound of water can do one foot-pound of work.

changes are taking place all around us. A clock spring is given potential energy when it is wound. It converts this potential energy into the kinetic energy of sound and eventually into heat, as the ticks of the clock agitate the surrounding air. The potential energy of coal may pass through the energy forms of heat (Figure 587), kinetic energy of moving steam particles, mechanical energy of the piston of

a steam engine, electrical energy from a dynamo, and eventually be radiated as heat and light from the incandescent lamp in your home.

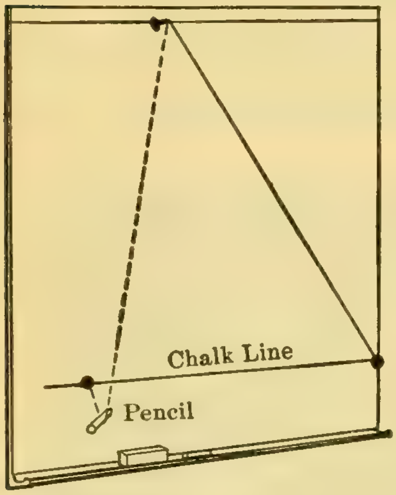


FIGURE 586. — CONVERSION OF ENERGY IN A PENDULUM.

If a pencil checks the swing of a pendulum, the bob swings up as high as the position from which it started.

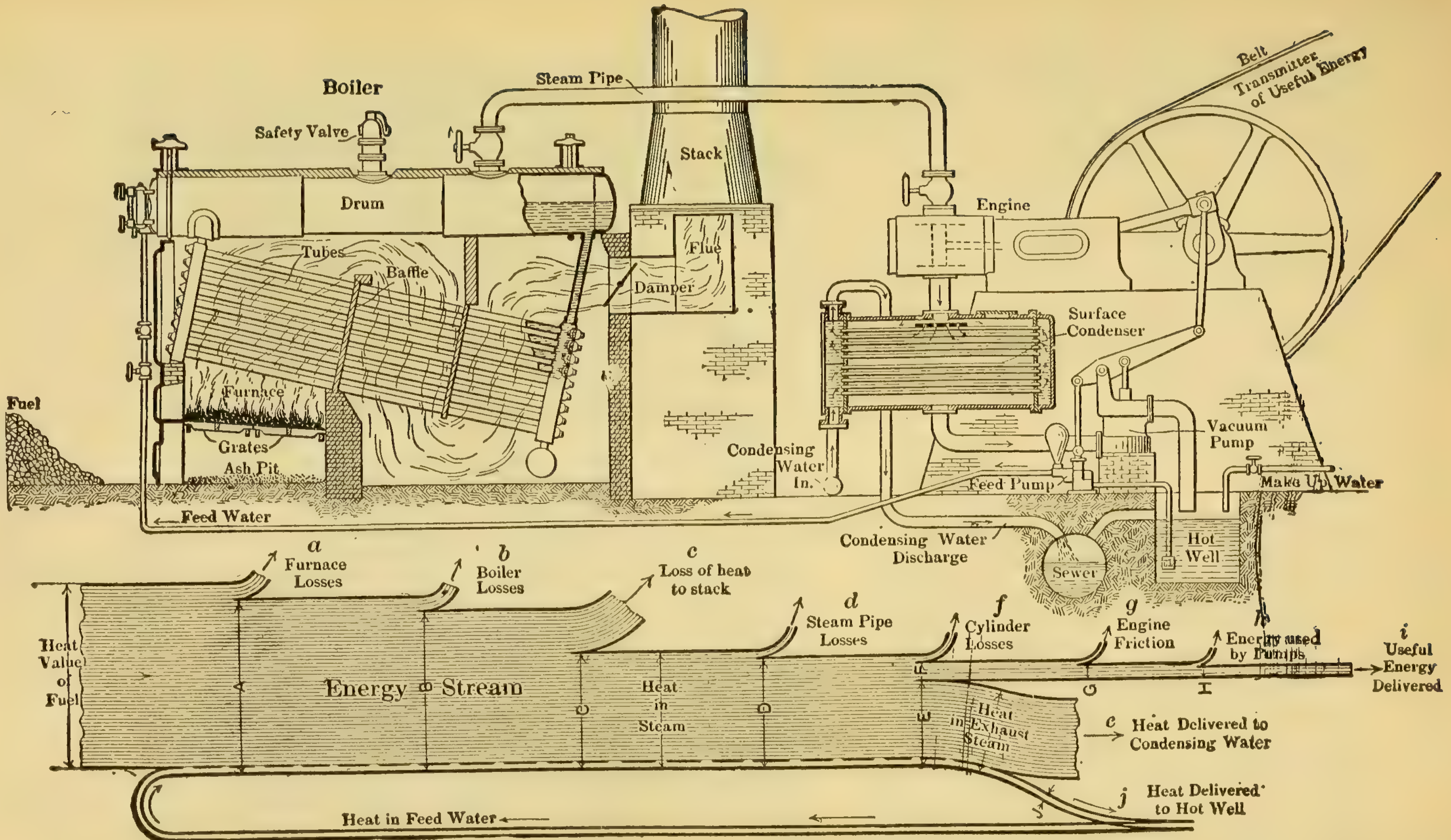
Most conversions of energy eventually leave the energy in the kinetic form. Since potential energy is the available, useful form, this change represents a continuous loss of available energy.

402. Dissipation of Energy. — The fact that energy cannot be destroyed does not mean that the available supply of energy is inexhaustible. Every change of potential into kinetic means a loss of available energy. A pound of coal represents 12 million foot-pounds of potential energy approximately. Now suppose the coal to be burned in the boiler of a steam engine under favorable conditions. About 10 million foot-pounds of this energy disappear into the atmosphere as heat. The 2 million foot-pounds which are usefully applied to operate machinery eventually are dissipated in the same way. The available potential energy of the coal has become unavailable energy in the form of low-temperature heat, and while there is just as much energy in the universe as before the coal was burned, the *available* energy is reduced by the 12 million foot-pounds.

QUESTIONS

1. In what two forms is energy found? How are the forms distinguished?

2. What factors determine the kinetic energy that a body possesses?



From Hirschfield and Ulbrecht. Steam Power. Courtesy John Wiley & Sons.

FIGURE 587. — DISSIPATION OF ENERGY IN A STEAM POWER PLANT.

The wastefulness of a steam engine is shown by the amount of energy lost before it reaches the place where it is to be used.

3. What equation shows the relation between kinetic energy and these factors?

4. A body possesses potential energy because its mass, molecules, atoms, or electrons are displaced either by separation or compression. Show that this is true for a charged condenser; for a tank of compressed air; for a stretched spring; for a wound clock spring.

5. What is the indirect source of all our energy? What are some of the direct sources?

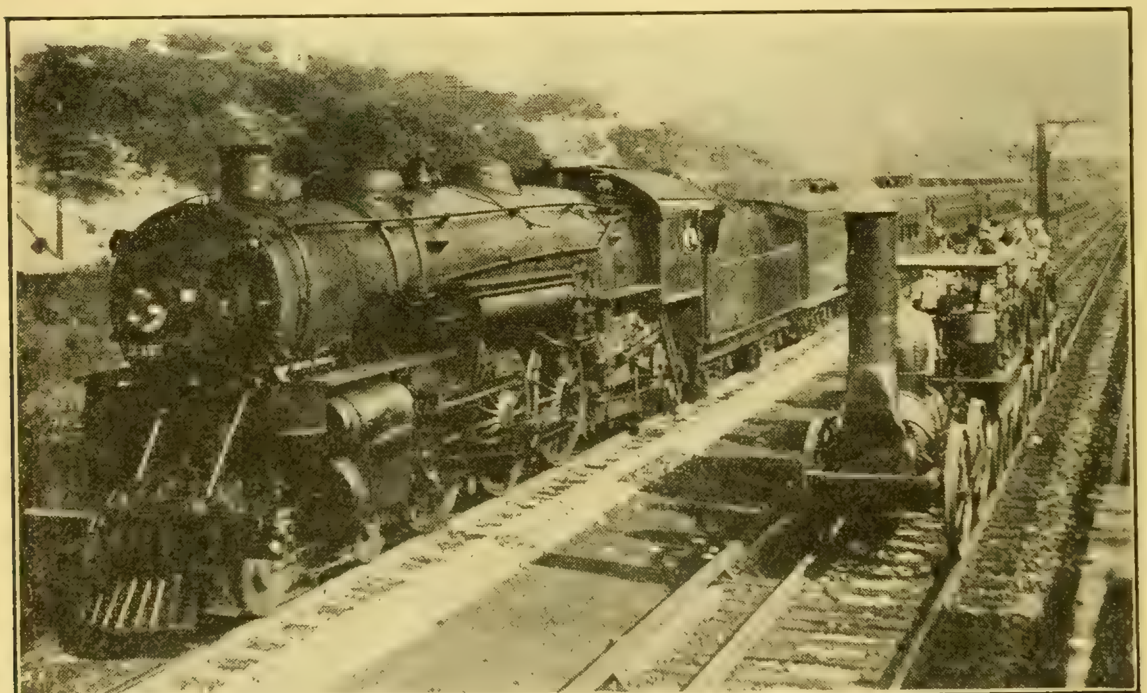
6. Are we using available energy faster or slower than it is delivered to us from the source?

7. Give an example of energy conversion that takes place in your home; in your body; in a moving train.

8. What effect do most energy conversions have upon the supply of available energy? Upon the total supply of energy?

POWER

403. Power Explained. — A man does work faster than a boy. A horse does work faster than a man, while an automobile engine does work faster than a horse. A boy may

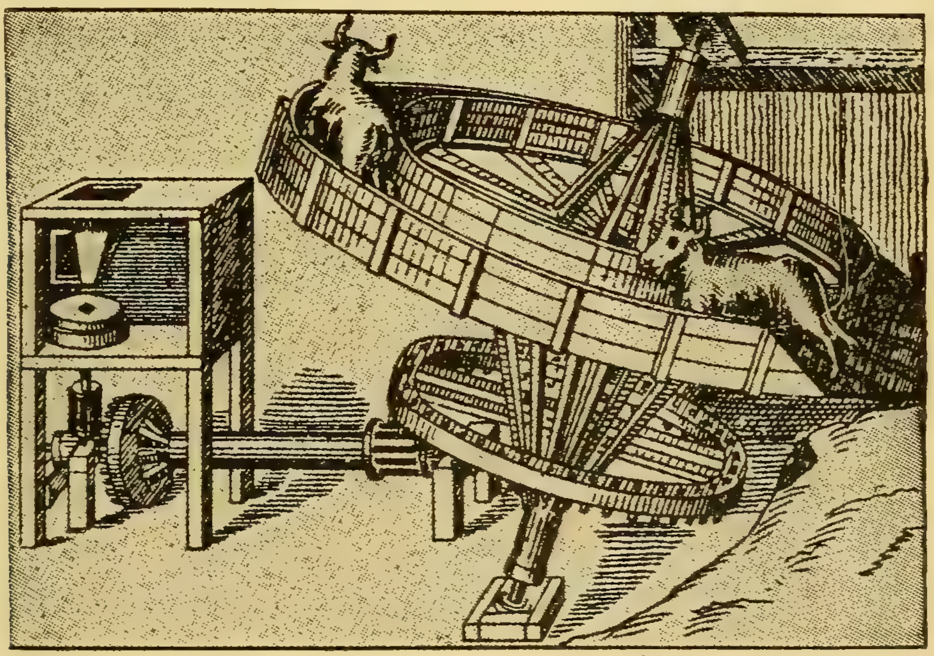


Courtesy N. Y. Central R. R.

FIGURE 588. — THE EARLIEST AND LATEST IN LOCOMOTIVES.
The modern engine surpasses the old one in power, since it can haul heavier loads faster.

agree to carry a ton of coal into a house. If he carries out his part of the agreement, he has done as much work as a man would do at the same task, although it may take the boy twice as long as the man. A certain amount of work is required to move a 1-ton automobile from one town to another. A horse might draw the car this distance in an hour while the engine in the car might do the same thing in 10 minutes. The boy differs from the man, and the horse from the engine in the time in which they do the same work or the time rate of working. *Power is the time rate of doing work.*

404. Power Units and Measurement. — Before the days of steam engines, horses or cattle were used in treadmills to



Courtesy Diehl Mfg. Co.

FIGURE 589. — AN ANCIENT TREADMILL.

Man at first used slaves or domesticated animals to turn his machines. Now his engines are driven by water, steam, or gasoline.

operate mine pumps and other machinery (Figure 589). As engines supplanted horses, they were rated according to the rate at which they could do work as compared to the horses which they replaced. In other words, their rate of work was

expressed in *horse power*. Since the power of horses varied, it was agreed that one horse power should represent the rate of work when 33,000 foot-pounds of work are done in 1 minute. Thus if an engine lifts 33,000 pounds 1 foot in 1 minute, it is doing work at the rate of 1 H.P. Or it may exert any number of pounds-force through such a distance that pounds $\times$ feet = 33,000 foot-pounds in 1 minute and still be doing work at the rate of 1 H.P. The expression for horse power in terms of feet, pounds, and minutes is then:

$$\text{H.P.} = \frac{\text{feet} \times \text{pounds}}{33{,}000 \times \text{minutes}}.$$

The other common units of power are the watt and the kilowatt. These units have been considered in § 263. One horse power is equivalent to 746 watts or to about $\frac{3}{4}$ of a kilowatt.

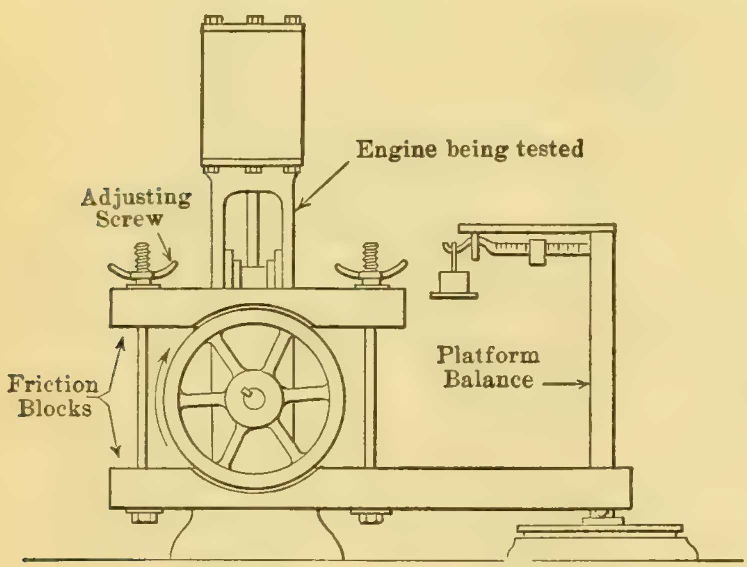
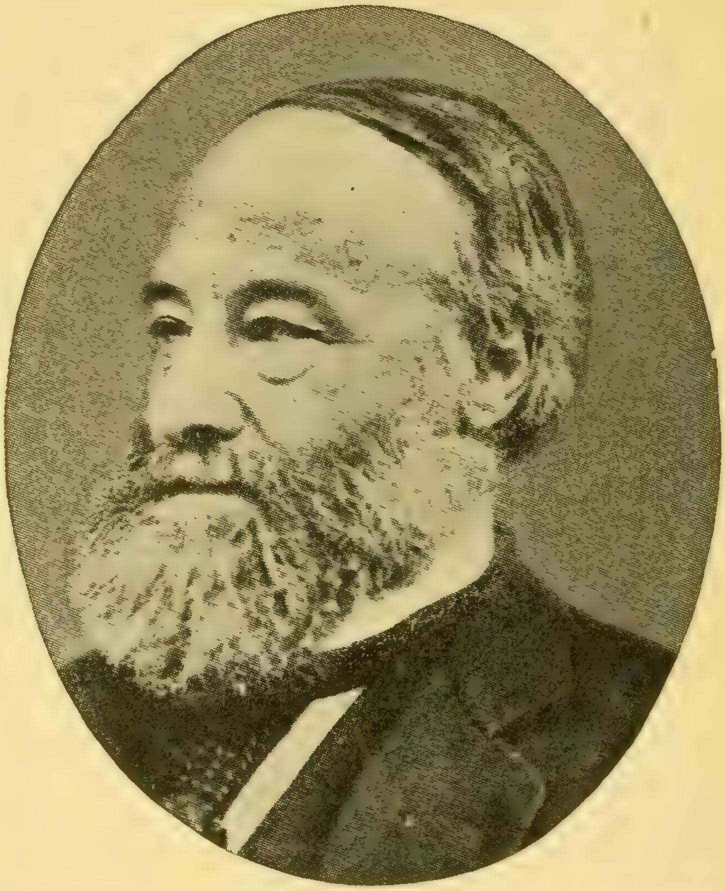


FIGURE 590. — PRONY BRAKE.

The adjusting screws regulate the friction applied by the blocks. The length of the brake arm is the distance from a point below the center of the axle to the point resting on the balance platform.

A man doing physical work is an engine converting the potential energy of food into useful kinetic energy. The power of laborers varies, but averages about one tenth horse power. The *output* of work is the *product* of the *time* of work and the *rate* of work.

405. Measurement of Power. — Engines of various kinds are tested by a Prony brake (Figure 590) or otherwise to



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James Prescott Joule (1818–1889) became interested at an early age in electricity and electromagnetism. This led him to seek a constant value for the units in which electrical quantities were measured. The work on measurement brought him to the question of the relation between the amount of heat produced by electric currents and then by other forms of energy. This work may be looked upon as the experimental work establishing the law of conservation of energy. Joule determined the constants involved when energy of one kind is converted into another; among these is the mechanical equivalent of heat: 778 foot-pounds = 1 British Thermal Unit.

determine their horse power. In the figure, two friction blocks partly encircle the pulley of the engine or motor to be tested. The end of the brake beam is supported by the platform balance. As the pulley wheel is rotated, the reading of the balance increases. The length of the brake beam is taken and the revolutions of the engine are recorded during a given interval. The engine is working against an opposition equal to the reading of the balance. It works against this opposition for as many feet as the beam would turn per minute, or $2\pi \times$ length of brake beam in feet $\times$ revolutions per minute (r.p.m.). According to § 404 the power of the engine will be found by:

$$\text{H.P.} = \frac{\text{feet} \times \text{pounds}}{33{,}000 \times \text{minutes}}$$

$$= \frac{(2\pi \times \text{beam length} \times \text{r.p.m.}) \times \text{balance reading}}{33{,}000}.$$

If the brake beam should describe a circumference of 15 ft, and the balance reading is 50 lbs, and if the engine under this load makes 110 r.p.m., then its horse power is

$$\frac{15 \times 110 \times 50}{33{,}000} = 2.5 \text{ H.P.}$$

An engine may not always do work at its rated horse power, but its rating should indicate the rate at which it may be made to do work safely and continuously.

Automobile engines are rated according to an arbitrary formula, which rarely gives the same result as the brake test. When climbing long steep grades, the engine may do work at its maximum power, but on the level it may do work at only a fraction of this maximum.

If all the energy of a pound of good coal could be utilized, it would furnish 1 horse power for about 6 hours. Under

very favorable conditions it may furnish 1 horse power for 1 hour. In a locomotive it furnishes 1 horse power for $\frac{1}{3}$ of an hour or less.

406. Force, Work, Energy, and Power. — To a student of elementary mechanics, these terms are likely to seem confused and overlapping. It is only by learning the distinctions between them and using them exactly, that they come to have clear, separate meanings. For the purpose of this treatment let us consider force as a push or a pull which may or may not change conditions. Work should be thought of as the action of a force through a distance. Energy, measured in the same units as work, differs from the idea of work only in that it represents ability to do work rather than the accomplishment itself. On the other hand, bodies possess energy only to the extent that work has been done on them. Work done upon a body results in energy being stored in the body. The expended work applied to the body must either give the body motion or produce certain displacements of electrons, atoms, molecules, or masses — displacements which represent potential energy. The energy stored as a result of work is able to do work again. Power stands out alone as the time rate of doing work.

SUMMARY

Energy is the capacity for doing work.

There are two kinds of energy, **kinetic** and **potential.**

Kinetic energy is the ability to do work because of **motion.**

Potential energy is ability to do work because of **displacement.**

Energy is measured in the same units as work.

Energy can neither be created nor destroyed (**Law of Conservation**).

Energy may be transformed from one kind to another. Dur-

ing the transfer of energy, while none is destroyed, some may become unavailable. Energy tends to become unavailable.

A body may possess only as much energy as has been expended on it.

Power is the **time rate** of doing work.

Power is measured commonly in horse power, watts, and kilowatts.

The horse power is the rate of doing work at 33,000 foot-pounds per minute.

EXERCISES

1. Define energy. Compare energy with work as to meaning and units of measurement.

2. Name and define two kinds of energy.

3. Classify as potential or kinetic the energy of: explosives; a moving train; coal; a charged Leyden jar; a hot iron; the air near a vibrating string; a wound clock spring; a lifted weight; a falling ball.

4. What two factors determine the kinetic energy that a body possesses? Give examples to make your meaning clear.

5. Compare the kinetic energy of a 25-pound shell moving 2000 ft/sec with that of a pile driver ram weighing 1000 lbs and moving 30 ft/sec.

6. What change is produced in the kinetic energy of a moving body if its mass is doubled? If its velocity is doubled?

7. Give four illustrations of kinetic energy not found in the questions above.

8. What causes matter to possess potential energy? What determines the potential energy possessed by a lifted weight or a stretched spring?

9. Give an example of potential energy resulting from the separation or displacement of electrons.

10. Give an example of potential energy resulting from the

separation of atoms. What is meant by the term *chemical energy?* Is it potential or kinetic?

11. With reference to what mass does a book on a table possess no potential energy? With what mass does it have potential energy? Explain.

12. Give three examples of the conversion of potential energy into kinetic energy.

13. Give three examples of the conversion of kinetic energy into potential energy. Which change is more common?

14. State the Law of Conservation of Energy and illustrate it.

15. Is there usually more or less available energy after any transformation of energy? Give an example.

16. What are four direct sources of energy?

17. What is the remote source of all the energy now available on the earth? Give the steps in one method by which this energy has become available.

18. Is available energy becoming greater or less in amount? Is available energy usually kinetic or potential? Why?

19. What is meant by the term *power?* With what other physical ideas is it frequently confused?

20. A contractor agrees to do the excavating for a certain building. Does it make any difference in the work done or in the power if he uses a steam shovel instead of manual labor? Explain.

21. Name two units in which power is measured. What rate of work is represented by one of these?

22. What element appears in power but not in work? How does an increase in this element affect the power required to do a certain amount of work?

23. Find the horse power of an engine that hoists 500 lbs of coal 55 ft in 10 sec.

24. How long will it take a 10-H.P. motor to raise a weight of 660 lbs to a height of 50 ft?

25. A 42-H.P. motor at full load lifts an elevator, whose unbalanced load is 1500 lbs, to the top of a skyscraper in 30 sec. How high is the elevator lifted?

26. Electric lamps are rated by the watts of power consumption. Does this indicate how much electrical energy is used or how fast it is being used?

27. Is the pay of a ditch-digger based upon his power or upon the work which he does? Explain.

28. What is the source of the energy of the human body? What becomes of this energy?

29. When a gun is fired, the gun and the bullet have equal momenta (Third Law). Do they have equal kinetic energies? Why?

30. Construct three or four sentences which will show the words *force, work, energy,* and *power* properly used in relation to each other.

CHAPTER XXX

ILLUMINATION AND ITS MEASUREMENT

407. Measurement of Light. — For centuries the common method of artificial illumination was by candles. These were often homemade and were, therefore, not standardized as to their ability to produce light. When whale oil, kerosene, gas, and electricity in turn replaced the candle, it was necessary to adopt a standard for the measurement of the light emitted by these various illuminants. This standard was naturally based on the candle, and a sperm candle seven eighths of an inch in diameter and burning 120 grains per hour is said to be a *standard candle* and to emit light at the rate of 1 *candle power*. Although these candles are still procurable for testing other lamps, a standardized electric lamp is generally used for this purpose. Electric lamps are now usually graded according to their power consumption in watts rather than by candle power, but artificial gas that is sold for illumination must be able to produce light of a certain candle power, when a given number of cubic feet of the gas are burned per hour.

408. Intensity of Illumination. — It is evident that if a number of persons are grouped about a single lamp each one does not receive the same illumination from the lamp. The person who sits nearest the lamp has his book or paper more brightly lighted than the one farthest from the source of light. The illumination of any surface depends not only upon the candle power of the lamp but also upon the dis-

tance from the lamp to the surface. The relation between intensity of illumination and distance of the source of light may be determined by the following experiment:

Experiment 147. — Procure a rectangular piece of stiff cardboard a few inches on each edge. On a wall or blackboard, lay off areas similar to the rectangle, but 1, 4, 9, and 16 times as large. Place an arc lamp at the side of the room opposite the marked-off wall and interpose the cardboard between the lamp and the wall, so that at different distances the shadow of the card will cover the different areas in turn (Figure 591).

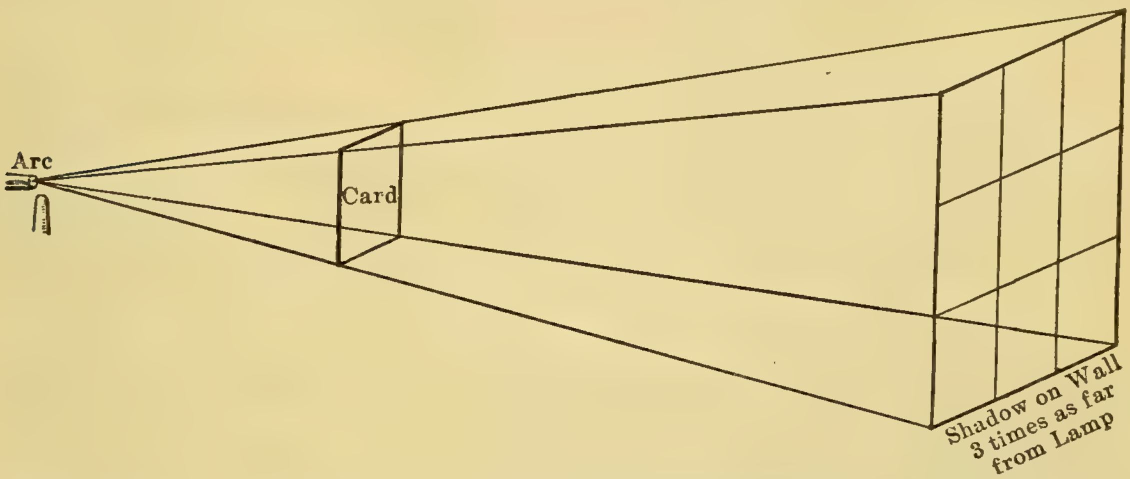


Figure 591. — The card at $\frac{1}{3}$ of the distance to the wall cuts off light from an area 9 times as great as its own.

Measure the distance from lamp to wall, and the different distances at which the cardboard was placed to shadow the areas laid off. It will be found that, in order to have the shadow of the cardboard cover an area as large as the cardboard itself, the cardboard must be placed against the wall. But in order to have the shadow cover an area 4 times as large as the card, the card must be $\frac{1}{2}$ the distance from the lamp to the wall. When the card is $\frac{1}{3}$ the distance from lamp to wall, the shadow will cover an area 9 times as large as the card, while in order to have the shadow cover the area 16 times the card, the card must be only $\frac{1}{4}$ the distance from the lamp to the wall.

Now a bit of reasoning is required to show us the relation between distance and illumination. In the first case, when the card was placed against the wall, the card was lighted just as brightly as the wall under it would be if the card were

removed. We may say, then, that the distance of the card is 1 and its illumination is 1. But when the card is midway between the lamp and the wall, the card's shadow covers an area 4 times as large as the card. The card then receives on its surface the same amount of light energy as would have covered 4 times as much surface on the wall, or the illumination of the card at a distance of $\frac{1}{2}$ is 4: at a distance of $\frac{1}{3}$, illumination is 9: at a distance of $\frac{1}{4}$, illumination is 16. The next numbers in the series would be $\frac{1}{5}$ and 25 times the illumination, $\frac{1}{6}$ and 36 times the illumination, and so on. As the number representing the distance becomes smaller, the number representing the illumination becomes larger, and conversely. But the illumination increases not in proportion to the decrease in distance but in the proportion of the decreased distance *squared.* From these two facts we may derive the law first stated by Kepler: *The intensity of illumination of a surface varies inversely as the square of the distance of the surface from the source of light* (**Law of Inverse Squares**).

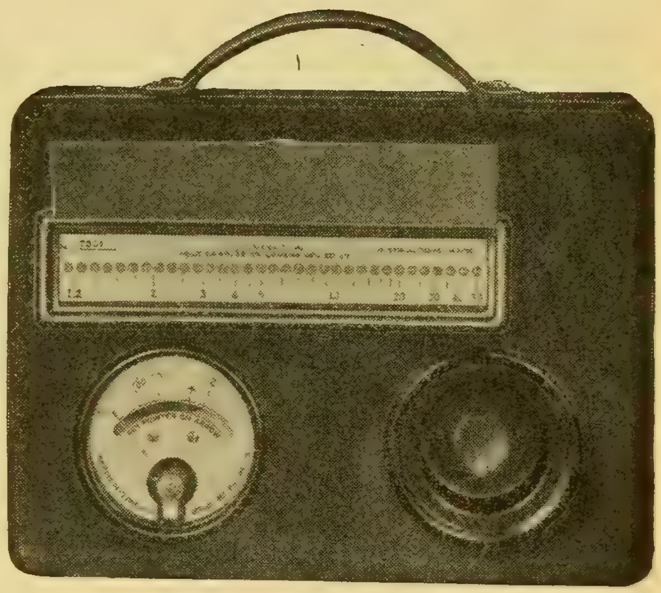
This relation may be seen by inspecting the numbers given above. To obtain the illumination of the card at any distance, it is only necessary to invert the fraction representing distance and then square this number to get the number representing illumination. For instance, $\frac{1}{2}$ (distance) inverted and squared becomes 4 (illumination), $\frac{1}{3}$ representing distance, inverted and squared becomes 9 representing illumination, and so on. If the card could be removed to a distance 3 times as great as the distance of the wall from the lamp, the illumination would be found by inverting 3 and squaring to obtain $\frac{1}{9}$ the illumination at this distance.

409. Foot-Candles of Illumination. — In the preceding section, we have discussed relative illumination with reference to distance from the source of light. Since most large build-

ings depend largely upon artificial illumination, it is necessary to have a unit for measuring illumination of various surfaces. This unit is the *foot-candle,* defined as the *intensity of illumination upon a surface 1 foot from a standard candle.* The foot-candles of illumination of any surface may be determined by dividing the candle power of the source of illumination by the square of the distance *in feet* between the surface and the source of light.

$$\text{foot-candles} = \frac{\text{candle power}}{\text{feet}^2}.$$

Any surface held 1 foot from a standard candle receives 1 foot-candle illumination. At 2, 3, 4, 5, and 6 feet from the standard candle the intensities of illumination would be $\frac{1}{4}$, $\frac{1}{9}$, $\frac{1}{16}$, $\frac{1}{25}$, and $\frac{1}{36}$ foot-candle respectively. A book held 3 feet from a 36-c.p. lamp receives an illumination whose intensity is $\frac{36}{9} = 4$ foot-candles. At 6 feet the book would receive $\frac{36}{36} =$ 1 foot-candle.



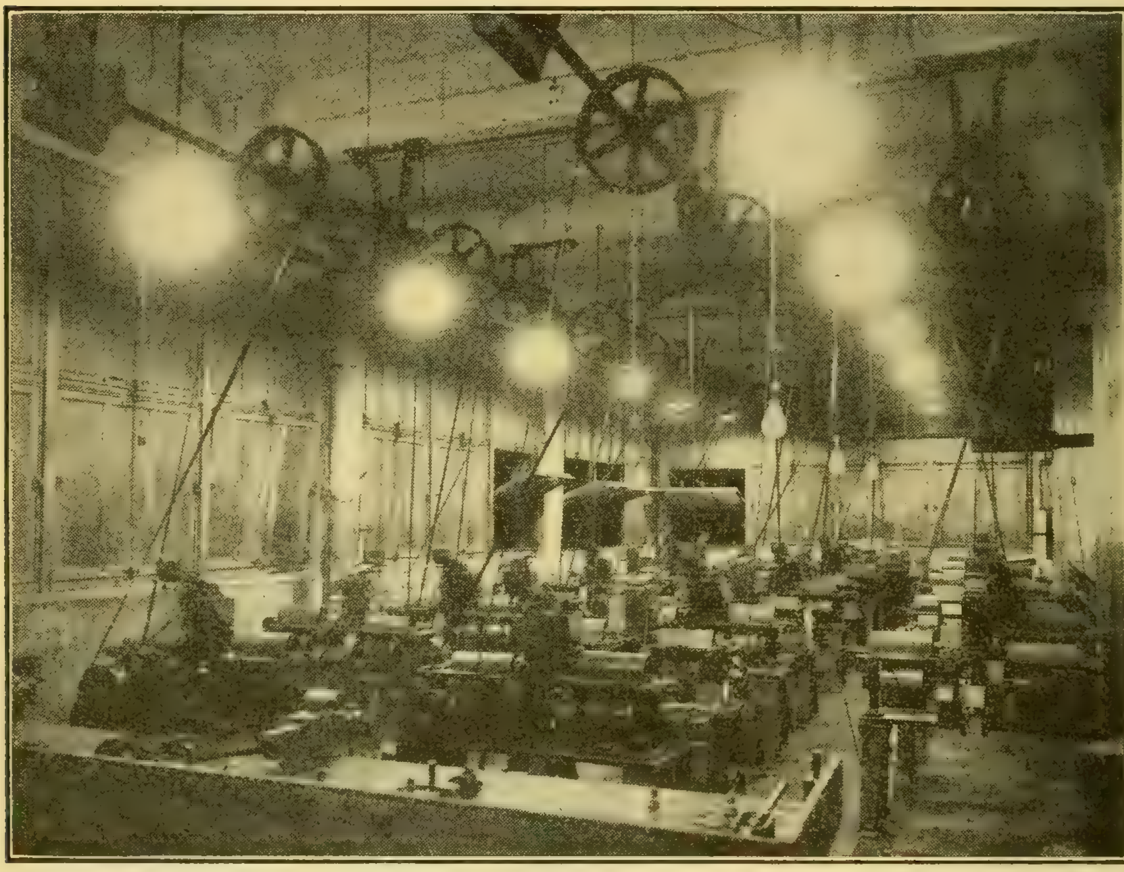
Courtesy G. E. National Lamp Works.

FIGURE 592. — FOOT-CANDLE METER.

This measures the illumination directly by comparing it with the illumination produced by a standard lamp in the meter.

410. Proper Illumination. — The eye is exceedingly adaptable to the wide variations of intensity of illumination. The pupil of the eye opens in dim lights to allow a larger beam of light to enter the eye and closes to shut out an excess of light when illuminations become too intense. But, since artificial illumina-

tion costs money, it is advisable to regulate the intensity of illumination according to the purposes to which the building is to be used. Halls and stairways are suitably illuminated when the intensity is $\frac{1}{2}$ to 1 foot-candle; an office building might require 2 to 3 foot-candles; for continuous reading,



Courtesy Edison Lamp Works.

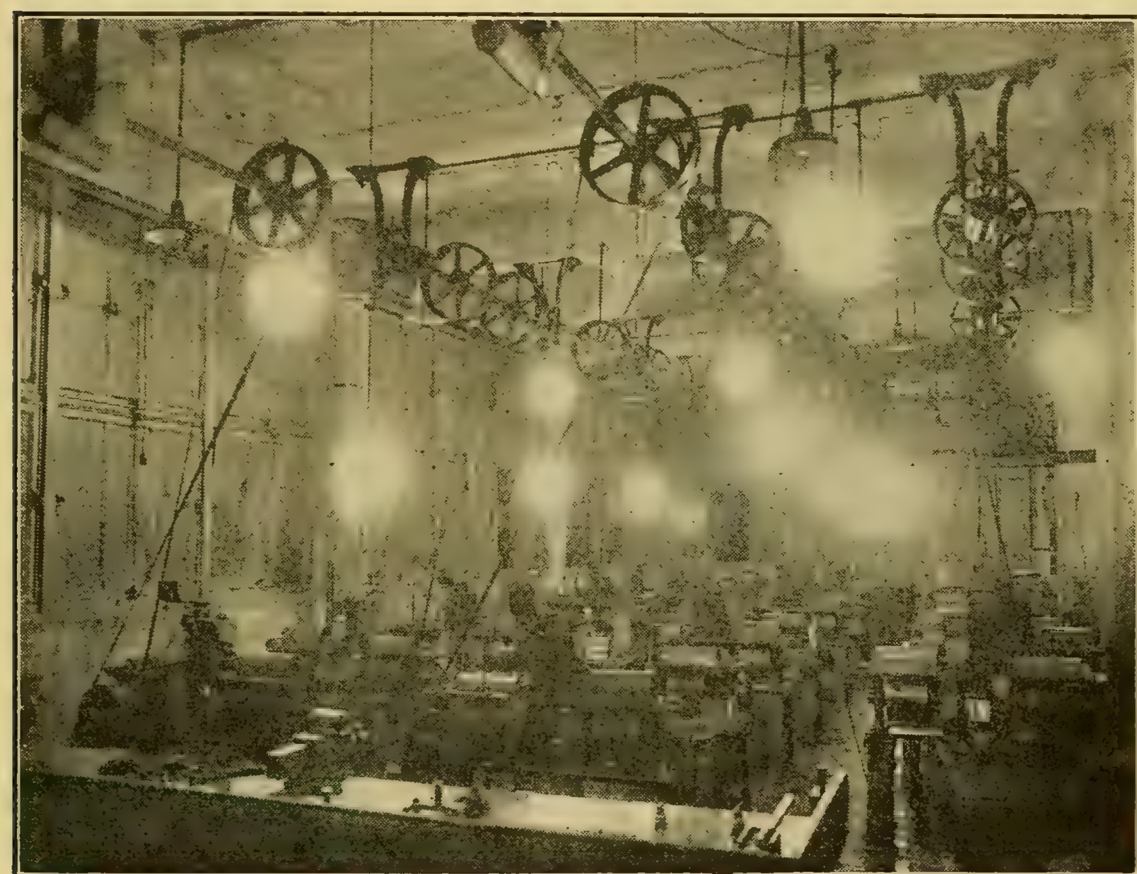
FIGURE 593. — A MACHINE SHOP PROPERLY LIGHTED.

A few high-power lamps, placed near the ceiling, give sufficient and uniform illumination.

3 to 4 foot-candles should be furnished; for sewing on light cloth, 5 to 6 foot-candles are needed; while workers on dark cloth need 7 to 8 foot-candles (Figure 592).

These figures are not strictly adhered to, either at home or in public buildings, but they represent a standard which experience has proved to be a safe one. Figures 593 and 594 show how important the proper placing of lamps is in securing proper illumination.

411. Measurement of Candle Power. — Having learned the meaning of the foot-candle, we may now apply this knowledge to the determination of the candle power of lamps. This determination must be made repeatedly by manufacturers of lamps, by testers of illuminating gas, and by engi-



Courtesy Edison Lamp Works.

FIGURE 594. — THE SAME SHOP POORLY LIGHTED.

Low-hung lights of smaller power give insufficient and uneven lighting.

neers and builders interested in the proper illumination of buildings. There are many complicated methods for the determination of candle power, but a simple method will indicate the fundamentals. For accuracy, all methods must have an invariable standard lamp with which the unknown lamp is to be compared, and a means of comparing the unknown lamp with the known lamp. The Rumford photometer used the shadows cast by the two lamps as a

basis of comparison. The Bunsen photometer has a card with a translucent grease spot, the card being moved between the standard lamp and the unknown lamp until the sides of the card are equally illuminated. The Jolly photometer is more accurate for an inexperienced person than either of these, because it is easier to form a judgment of the equality of illumination of its two sides.

The Jolly photometer (Figure 595) is made by placing a sheet of tinfoil between two similar blocks of paraffin about

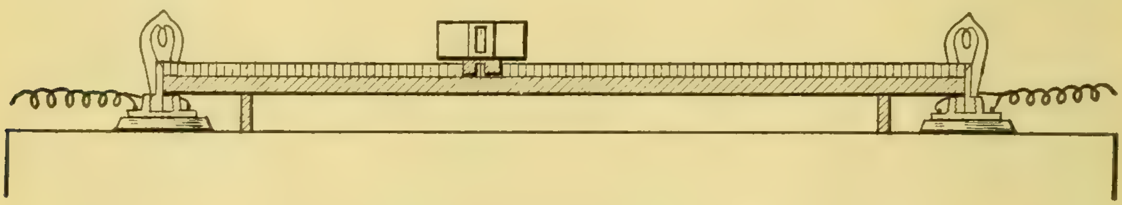


FIGURE 595. — JOLLY PHOTOMETER.

This gives candle power in one direction only.

one half inch thick. These blocks are in a rectangular box with ends open to the two lamps and having an aperture cut in the side so that an observer may see the edges of the two blocks. This box is placed between the standard lamp and the unknown lamp and moved until the two blocks of paraffin are equally lighted. The distances from the lamps to the tinfoil screen are then measured.

The screen shows that upon its two sides the two lamps are producing equal illumination, or:

$$\text{foot-candles} = \text{foot-candles}$$

So the candle power may be calculated from the formula $\frac{\text{c.p.}}{\text{d}^2} = \frac{\text{C.P.}}{\text{D}^2}$, in which the small letters may represent the candle power and the distance of the standard lamp, and the capitals represent the candle power and distance of the

unknown lamp. Since three of these four quantities are known, the fourth, which is the candle power of the unknown lamp, may be determined by the ordinary method of solving fractional equations.

If the standard lamp has a candle power of 16, and if, to secure equal illumination, the screen must be placed 2 feet from the standard lamp and 3 feet from the unknown lamp, then the candle power of the unknown may be found by the equation $\frac{16}{2^2} = \frac{x}{3^2}$, then $4x = 144$, and $x = 36$, the candle power of the unknown lamp.

Courtesy Electrical Testing Laboratory.

FIGURE 596. — SPHERICAL PHOTOMETER.

The lamp under test is in the large sphere. Its average light in all directions (spherical candle power) is found. Means for control of voltage are seen in front.

The photometers described above give the candle power in one direction only. A more useful measurement is the mean spherical candle power, that is, the average candle power in all directions (Figure 596).

SUMMARY

Light emission is measured in **candle power**, the rate at which light is emitted by the standard candle.

Intensity of illumination is measured in **foot-candles**, the brightness of a screen 1 foot from a standard candle.

The intensity of illumination upon any surface varies **inversely**

as the square of the distance between the surface and the source of light. This is the **Law of Inverse Squares.**

Candle power is determined by a photometer, to which is applied the equation:

$$\frac{\text{c.p.}}{\text{d}^2} = \frac{\text{C.P.}}{\text{D}^2}$$

Proper illumination varies from 2 to 10 foot-candles, according to the work to be illuminated.

EXERCISES

1. What is meant by *candle power?* What is the necessity for such a unit?

2. Distinguish between *light* and *illumination.* What is the unit of measurement of illumination?

3. If you are holding your book 6 ft from a lamp, and then move it to one half this distance, how much better will your book be illuminated? How well at twice the original distance?

4. State the law showing the relation between illumination and distance. What words do you think should be emphasized in stating it?

5. Describe the experiment and give the reasoning by which the Law of Inverse Squares is derived.

6. What is a *foot-candle?* How may the foot-candles of illumination on any surface be found, if the candle power of the source and the distance from the source to the surface is known? Illustrate by the use of numbers.

7. Give two ways by which the number of foot-candles of illumination on a desk could be increased.

8. Would you use for a reading room in a library one large, centrally located lamp, or a small one for each table? Give a reason for your answer.

9. What would be the intensity of illumination on a book placed 4 ft. from a 32-c.p. lamp? At what distance from the lamp will the illumination be four times as much?

10. What intensity of illumination is desirable for a hallway? A reading-room table? A machine-shop lathe? A sewing machine?

11. How is the screen of a Jolly photometer constructed? Where should the screen be placed when determining the candle power of a lamp?

12. Describe some other form of photometer, and tell how you would use it in determining the candle power of an unknown lamp.

13. What measurements must be made on a Jolly photometer in determining candle power? If the screen is equally illuminated by a lamp of 30 c.p. at a distance of 40 cm and an unknown lamp at 60 cm, what is the candle power of the unknown?

14. Find the candle power of a lamp which, at 40 cm from a screen, gives equal illumination with a 20-c.p. lamp at 50 cm.

15. A screen is placed between a 16-c.p. lamp and a 32-c.p. lamp at a distance of 2 ft from the smaller lamp. What is the distance between the lamp on the other side and the screen, if the two sides of the screen are equally illuminated?

16. Find the distance at which a 48-c.p. lamp must be placed in order to illuminate a screen as brightly as a 20-c.p. lamp at 40 cm.

17. What is the candle power of a lamp placed 120 cm from a screen equally illuminated by a 16-c.p. lamp at 80 cm from the screen?

18. How many times will your illumination be bettered by moving your book from a distance of 10 ft from a lamp, to a distance of 2 ft? If the lamp is a 40-c.p. lamp, express your results in foot-candles.

19. One candle is placed at one end of a meter-stick and four similar candles at the other end. Where must a screen be placed on the stick to be illuminated equally by the two sources of light? (NOTE: Let x = distance from the one candle to the screen, and $1 - x$ the distance from the screen to the 4 candles.)

20. Solve the preceding problem, using 1 candle at one end of the stick and 2 candles at the other.

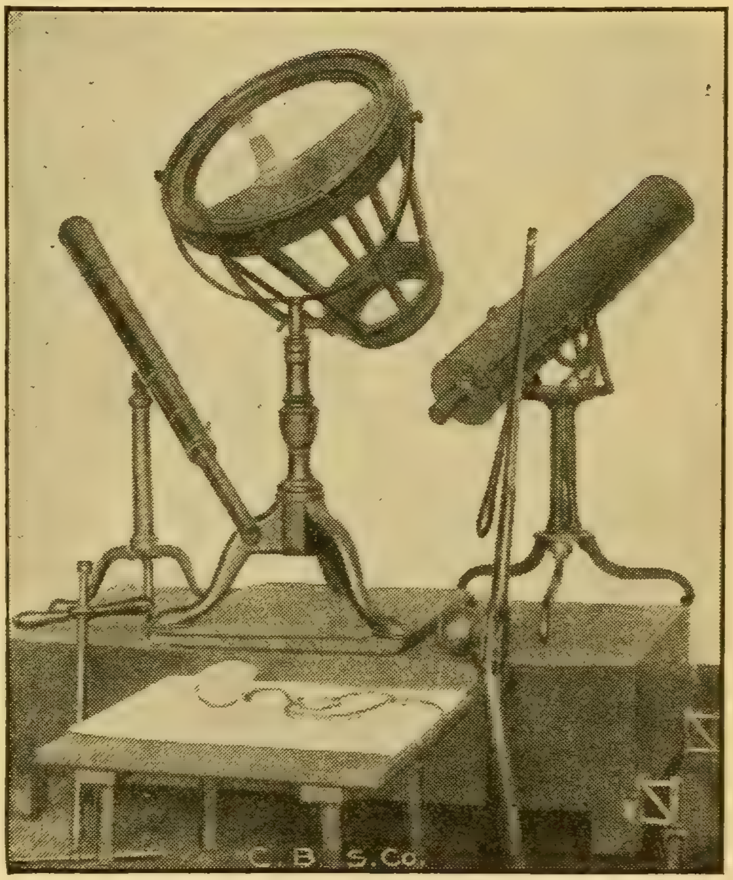
21. A screen is placed midway between two candles and then one candle is moved so it is 4 times as far from the screen. How many similar candles must be put with it to balance the illumination on the screen?

CHAPTER XXXI

LENSES

412. Historical. — There is no more interesting and important topic in light than that of lenses. The subject interests us first because of its relation to the formation of images by the eye; and also because of the great number of optical devices, such as spectacles, cameras, moving-picture lanterns, telescopes, and microscopes, all of which depend upon lenses for their usefulness to us.

Moreover the subject is of historical interest to us, for it is possible that lenses were known to the Greeks, at least as burning glasses (Figure 597).



Courtesy Cambridge Botanical Supply Co.

FIGURE 597. — PRIESTLEY'S INSTRUMENTS.

The large lens is the one he used as a burning glass in obtaining oxygen for the first time. The others are telescopes.

In 1560 Battista Porta, a boy of fifteen, published an account of the construction of the pinhole camera (*camera obscura*, see § 174). In the opening of

the box, he placed a lens and found he could obtain images which were both clearer and brighter than those obtained without the lens. He also suggested that the eye was like his camera, having an opening with a lens across it and a wall upon which images were formed. Kepler completed this comparison by a careful analysis of the parts of the eye.

The progress in other branches of science has been aided greatly by the development of such optical instruments as the

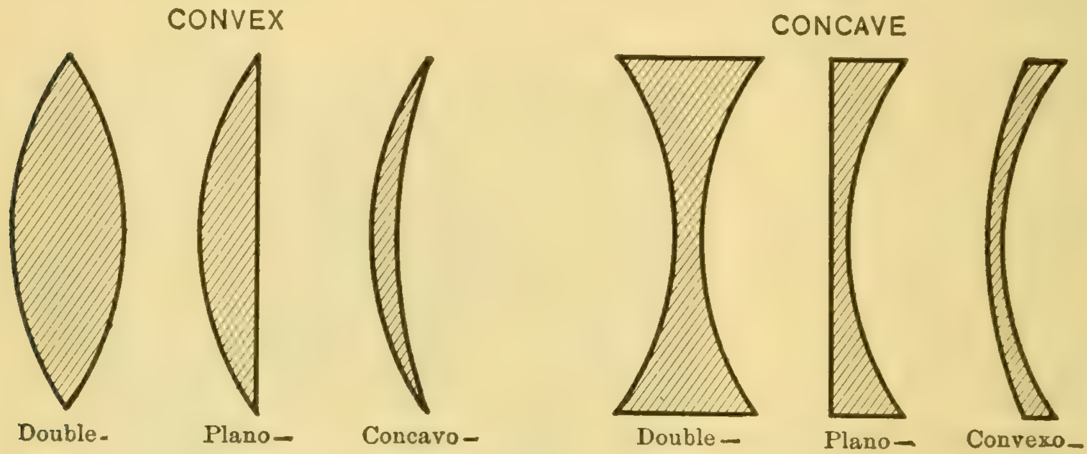


FIGURE 598. — Common forms of simple lenses.

microscope, which opened up a new world of interest to biology and medicine; the telescope, which revealed many secrets of the skies; and the camera, which is an indispensable accessory of both.

413. Kinds of Lenses. — There are two types of simple lenses; those *thicker* in the middle than at the edges, called *convex*, and those *thinner* in the middle, called *concave*. These may be further divided into double convex, plano-convex, and concavo-convex, and the corresponding concave forms (Figure 598). The general effect of convex lenses is to converge the light that falls upon them or to render it less divergent. The general effect of concave lenses is to cause light to be more divergent than before it falls upon the lens.

414. Explanation of Concave Lenses. — Concave lenses are not so common as convex lenses, but we often see them in the spectacles worn by nearsighted persons. The eyes of the wearer of such spectacles appear to be much diminished in size. We find that concave lenses form small images, which do not differ greatly in appearance from the object.

To explain the effect of the lens upon the light, we must first obtain a clear idea of the movement of light. Any

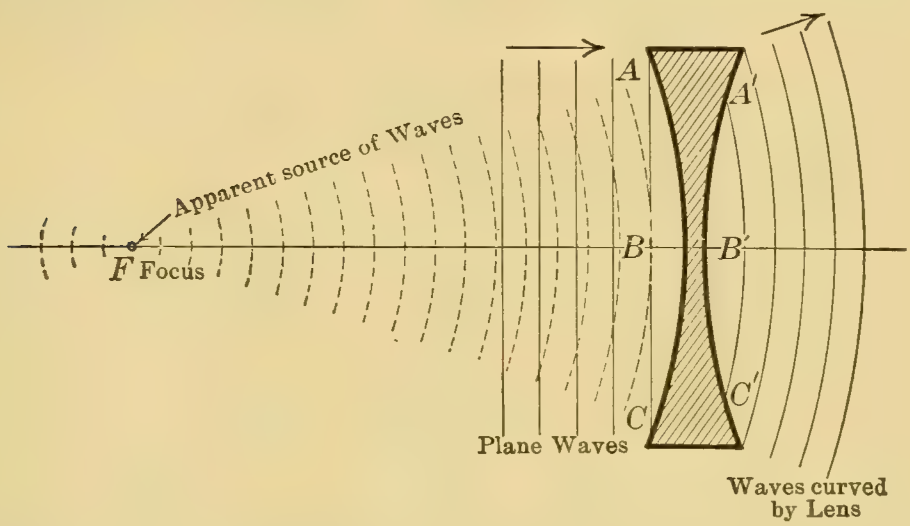


FIGURE 599. — A plane wave at the left, on passing through the lens, becomes a curved wave *appearing* to have its source at *F*.

visible object sends out waves of light, just as a disturbance on the water surface sends out water waves. There is this difference, however, that all the water waves lie in the horizontal plane of the surface of the water, while the light waves spread in all directions — above, below, right, left, front, and back. While the water waves are circular in outline, the front of the light wave is spherical. Both waves, however, become flatter and flatter as the wave proceeds farther from the source. As a result of this flattening, we may consider that any light wave that has advanced a short distance, say 100 feet from its source, has no longer a curved front, but a straight or plane front. Light waves near their source are

curved; light waves distant from their source have plane wave fronts.

Suppose a plane wave ABC to fall upon a concave lens (Figure 599). The edges of the wave, A and C, reach the glass before the center, B, reaches it. The speed of light in glass being less than in air, the edges A and C are retarded so that B advances farther in a given time than they do. The emerging wave has the front $A'B'C'$. This wave appears to come from a point much nearer the lens than the actual

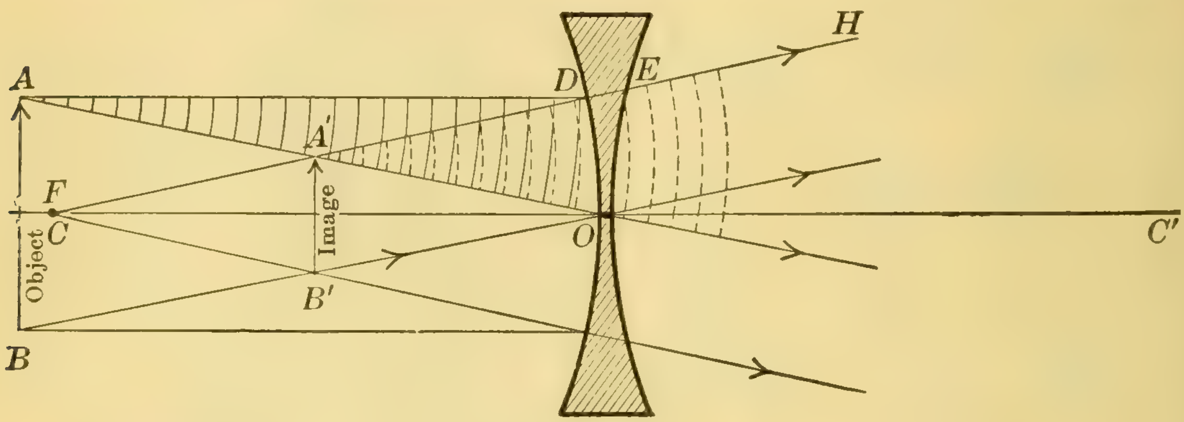


FIGURE 600. — Rays AO and AD diverge more widely after passing through the concave lens. Waves from A and B *appear* to come from the virtual image $A'B'$.

origin of the wave, while the light leaving the lens is much spread out or diverged.

415. Image Formed by a Concave Lens. — The character of an image formed by a concave lens may be determined by the study of the preceding explanation and the accompanying figure (Figure 600). In this figure, C and C' are the centers from which the curved surfaces bounding the lens are drawn. The line CC' is the *principal axis* of the lens. O is the *optical center* of the lens, the only point in the lens through which a ray of light may pass without refraction. F is the *principal focus* of the lens, which for a concave lens means the point from which all rays parallel to the principal axis *appear* to

come. From point A of the object AB, let us consider the part of the wave emerging from A between the line AD, parallel to the principal axis and the line AO, passing through the optical center. The narrow portions of the light wave moving along AD and AO may be called *rays*. By the definition above, we find that the ray moving parallel to CC' must be refracted so as to appear to come from the principal focus F, while the ray passing through O goes on its way without deviation. The emergent rays will lie along the paths EH, and AO prolonged, making allowance in the first case for a second refraction as the ray reënters the air. But these two rays, and hence all portions of the wave coming from point A, *appear* to originate at the point A'. By a similar construction, all the light reaching the lens from B appears to come from B'. An observer on the right-hand side of the lens may then see at $A'B'$ an imaginary or virtual *image* of AB, which must be smaller than AB, erect, nearer the lens than the object, and on the same side of the lens as the object. No matter how far AB is from the lens, the light emerging from the lens can only appear to center at some position like $A'B'$ and so, while the image may change in size and position somewhat, it can never be a real image. The *real* light has passed through the lens without reaching a real focus.

416. Explanation of the Convex Lens. — Nearly every physics student has used a convex lens as a magnifying glass or in a camera, or has seen the large images thrown on the screen at the movies. The lens may then form several kinds of images, according to the distance that the object is placed from the lens. In each case, however, the lens does the same thing to the light that falls upon it, that is, it tries to overcome the divergence of the light and render it convergent if

possible. Recalling the discussion of curved and plane wave fronts, let us consider the effect of the lens upon light coming from a source so distant that its wave front is plane. Sup-

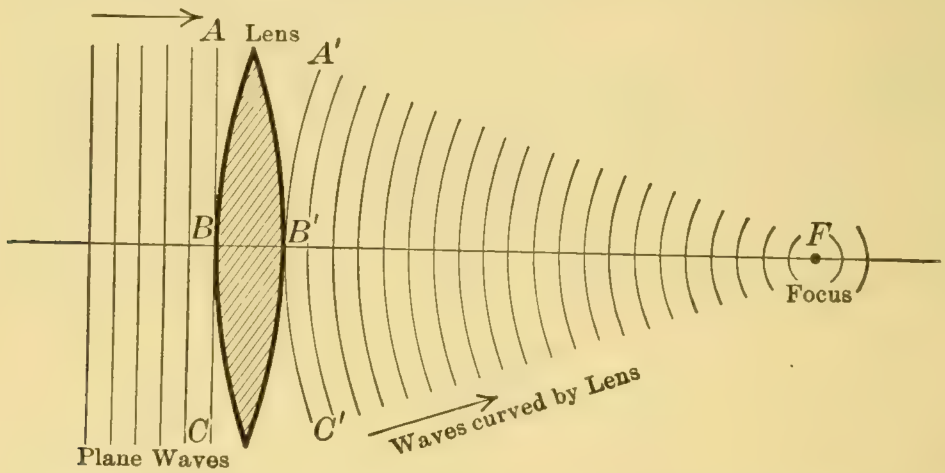


FIGURE 601. — The plane waves from a *distant* source at the left are given a curvature opposite to that with which they started. These reversed curves center at *F*, where a real image of the distant object appears.

pose (Figure 601) such a wave with a front ABC to fall upon the lens. B, reaching the glass first, is retarded, while A and C are still traveling with their original speed in air. A and C, passing through a thin portion of the lens, are slowed up

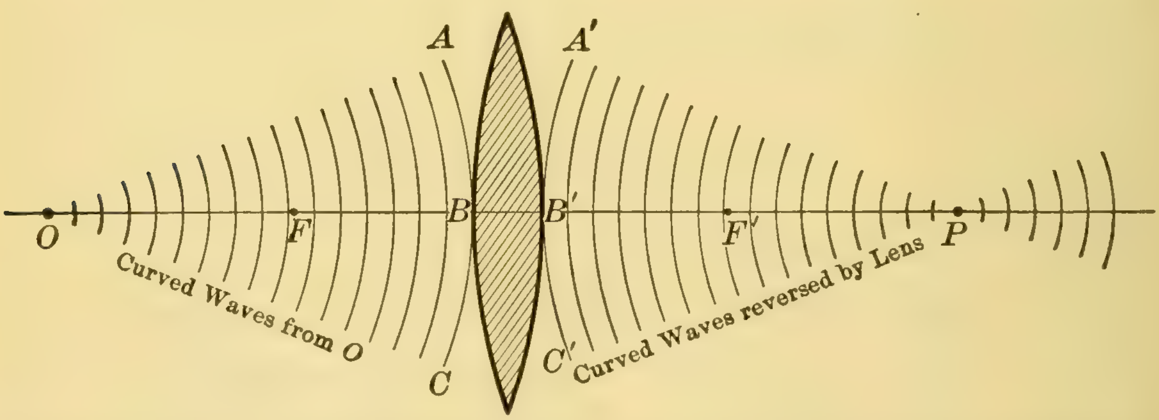


FIGURE 602. — Spherical wave fronts from a relatively near object, *O*, are reversed by the lens to form a real image at *P*.

but little and therefore gain on B, which must traverse the thickest part of the lens. By the time that B emerges from the lens at B', the light from A and C has advanced to $A'C'$.

The emergent wave has a front whose curvature is indicated by $A'B'C'$. This wave converges through the point F, the principal focus, and then diverges as indicated.

If the source of light is a finite distance from the lens, the wave front will still be curved when the light reaches the lens. Suppose the light to come from a point near the lens but more remote than the principal focus (Figure 602). The curved wave front ABC falls upon the lens with B reaching the lens before A and C do. This curvature will be reversed by the lens and the emergent wave will have a front indicated by the line $A'B'C'$. This reversed curve converges at point P and diverges again beyond it.

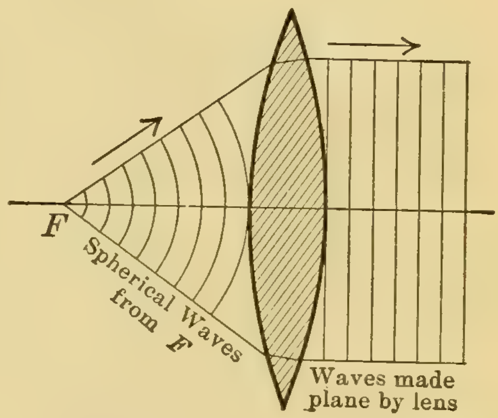


FIGURE 603. — Spherical wave fronts from F, the principal focus, are so sharply curved that the lens is only able to render them plane. This light does not focus, and hence forms no image.

If the light emerges from the principal focus F (Figure 603), the front of the wave will have exactly the amount of curvature that the lens is able to neutralize. The emergent wave front will be plane and the center of this plane wave is at an infinite distance from the lens — in other words the lens has failed to converge the light to a focus.

It is evident that if the light from some point inside the focus falls upon the lens, the curvature of the wave front is bound to be more than the lens can neutralize (Figure 604). In spite of the fact that B has to pass through a thicker portion of the lens than A and C pass through, B still emerges from the lens long enough before A and C emerge to give the front a curvature indicated by $A'B'C'$. This curvature is in the same direction as before the wave reached the lens, and

hence the wave appears to focus at point P, while in reality the light is not converged at all, but passes on beyond the lens still diverging.

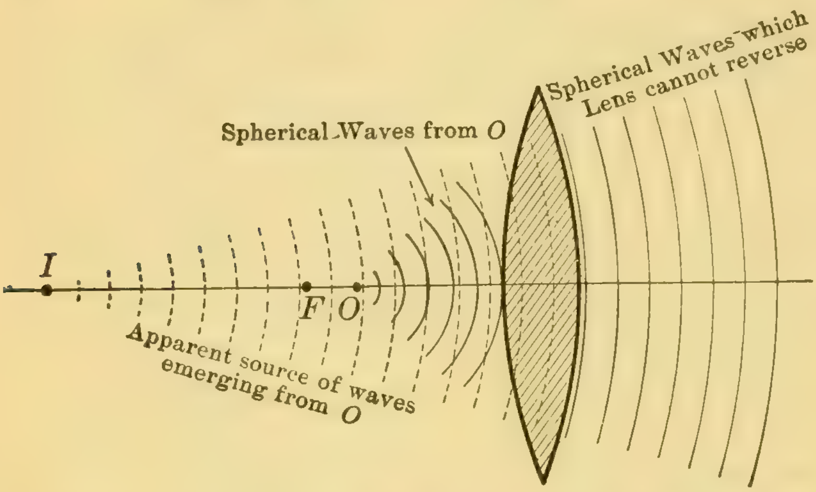


FIGURE 604. — The sharply curved waves from O, inside the principal focus, appear to come from I. The light at the right of the lens is still diverging, and the apparent source of the light, I, is the *virtual* image of O.

417. Convex Lens Images. — The definitions for the points of reference are the same for the convex lens as for the concave, with the exception of the principal foci. For a convex lens, these represent points *where light parallel to the principal axis actually converges.* A *ray* we will define again as a narrow portion of a wave front. Let us now divide the image formation by the convex lens into separate cases according to the distance of the object from the lens.

Case I. — We can determine the position and character of these images by experiment.

EXPERIMENT 148. — Mount a lens on a meter stick, and on the side of the lens away from a window, mount a card to serve as a screen (Figure 605). Select some object, as a chimney or a tree, that is sharply defined and more than 100 feet away. Light from this object may be considered to have a plane wave front at the lens, and, if the lens is held at right angles to the advancing light, the light will move parallel to the principal axis of the lens. Move the screen back and forth until the clearest image is seen upon the screen.

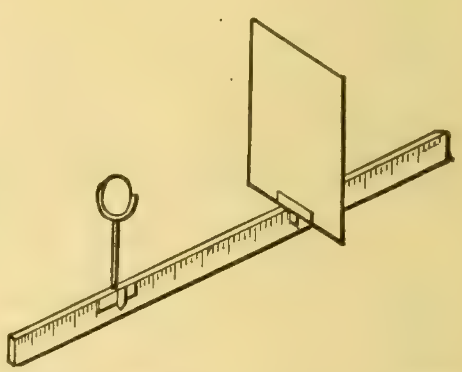


FIGURE 605. — LENS AND SCREEN FOR FINDING PRINCIPAL FOCUS.

Is the image erect or inverted? Of what size compared with the object? Is light really focused upon the card? If so, is the image real or virtual? What is the definition of principal focus? At what point is the image formed? . By measurement of the distance of lens to image, determine the focal length of the lens.

This experiment shows the kind of image, *small and real,* formed by a convex lens when the object is far enough away

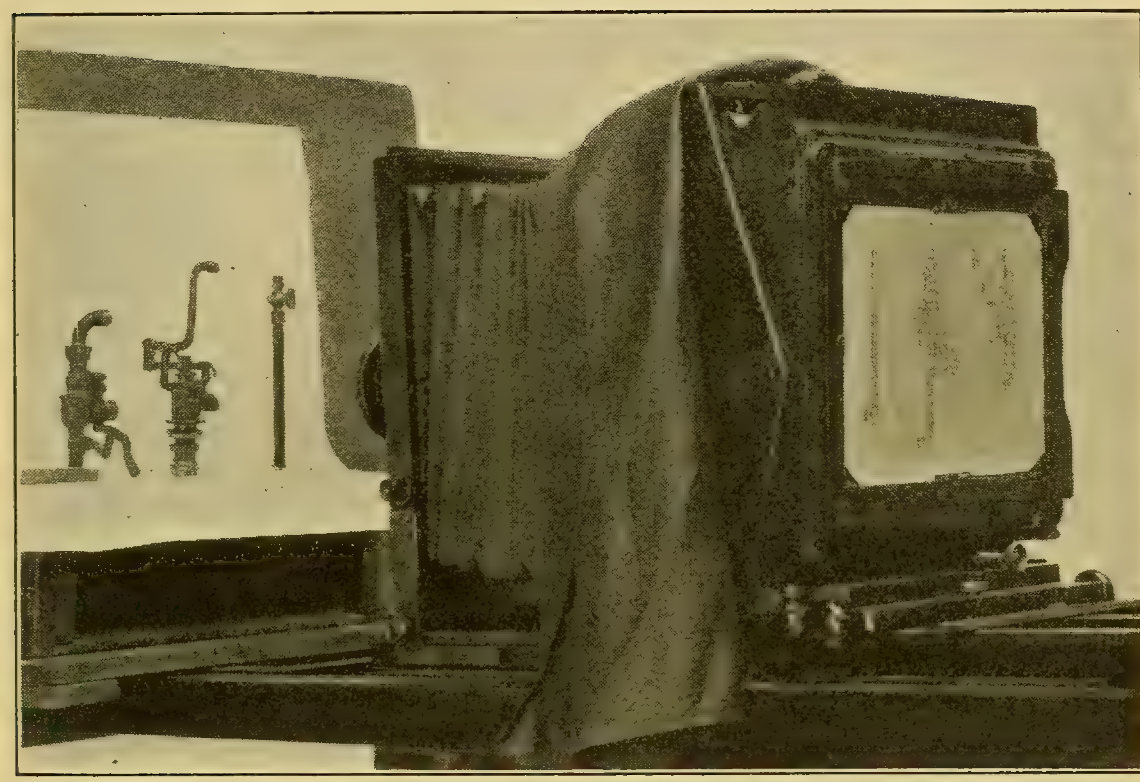


FIGURE 606. — A FOCUSED CAMERA.

A camera forms inverted real images. The image may be inspected on a ground glass plate before being permanently recorded on the negative.

so that parallel rays with a straight wave front reach the lens. It also shows a method of finding the principal focus and the focal length of the lens.

418. Case II. — A camera is generally used to obtain small images of objects (Figure 606). These images are formed upon a sensitive plate, or film. The light focused upon the plate starts the decomposition of a silver salt and "developing" makes a permanent image upon the plate.

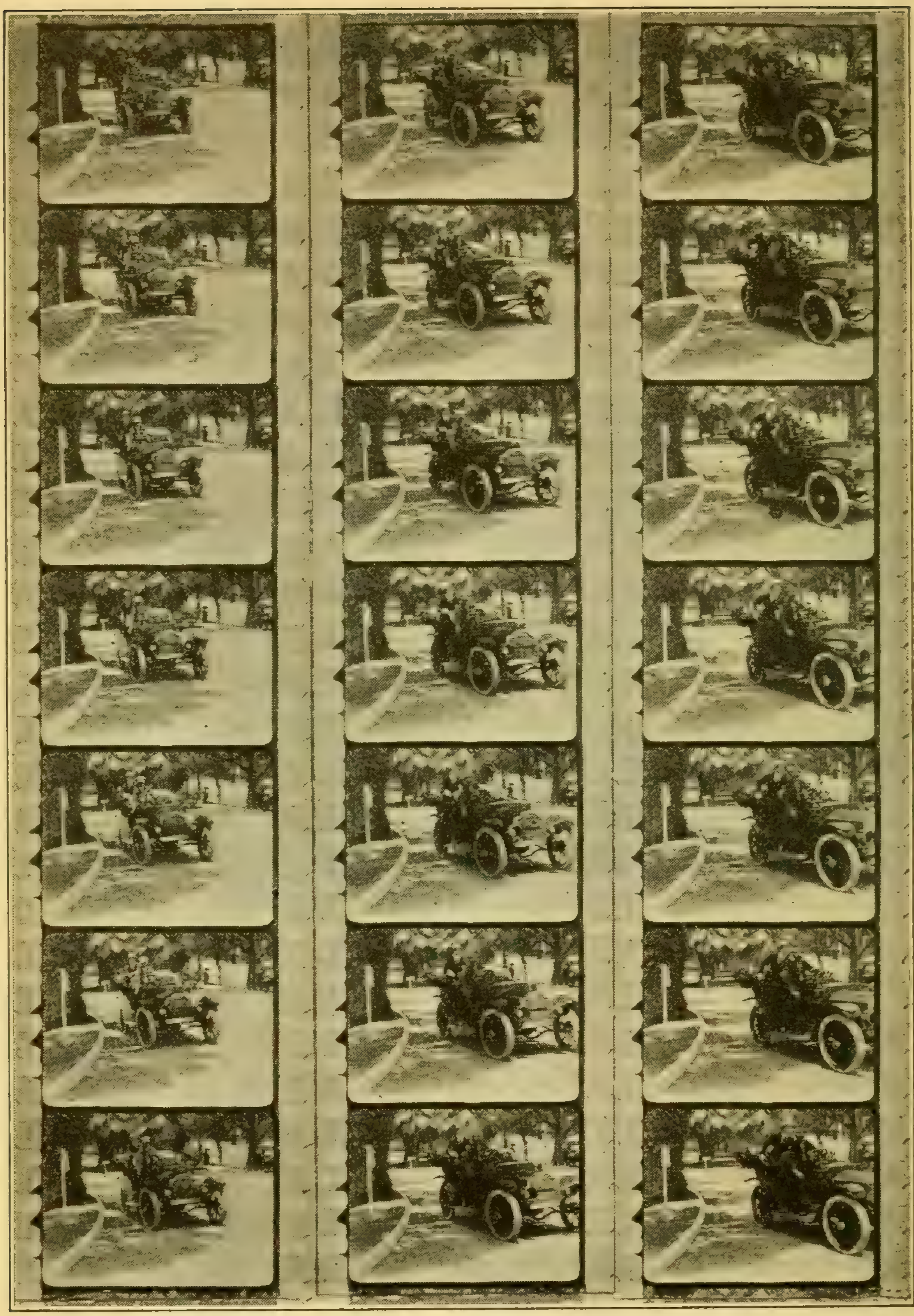


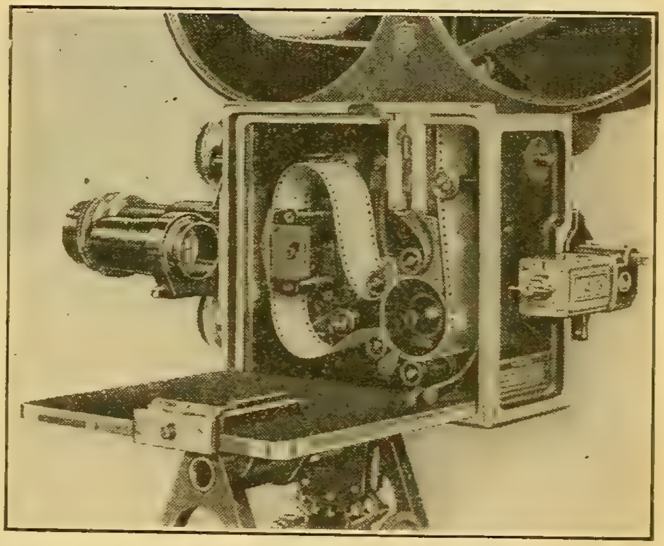
FIGURE 607. — STRIPS OF MOTION PICTURE FILMS.

Note the changes in position of the automobile in the successive pictures.

An experiment will show how these images are formed upon the plate.

EXPERIMENT 149. — Using the lens, stick, and screen as in the previous experiment, place a lighted candle, or an incandescent lamp, as the object at a distance of more than two focal lengths from the lens. Adjust the screen until the image of the candle flame is seen clearly upon the screen. *Compare image with object as to size and distance from the lens. Is the image erect or inverted? Is the image real or virtual?* A measurement of the distance of the image from the lens will show it to be more than one focal length but less than two focal lengths from the lens.

In order, then, that a camera lens may form a diminished, real image of an object, it is necessary that the object shall be more than two focal lengths from the lens. The farther the object is from the lens, the nearer is the image to the lens and the smaller it is. The limit of approach of the image to the lens is the focal length, which is reached when, as in Case I, the object is placed at a distance great enough to allow plane waves from it to reach the lens.



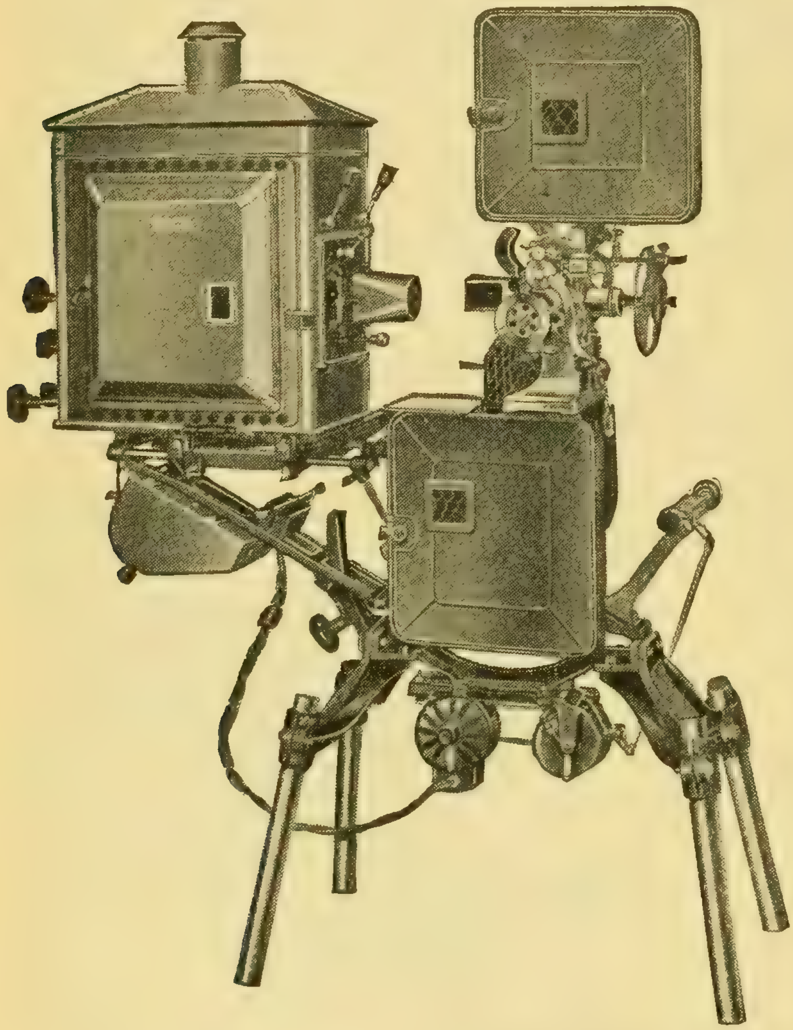
Courtesy Bell-Howell Co.

FIGURE 608. — MOTION PICTURE CAMERA.

A portion of the film is moved into place by a toothed wheel; the shutter opens and an image is formed on the film; the shutter closes, and the next portion of the film is moved into place behind the lens.

419. Case III. — The moving-picture lantern forms on a distant screen an enlarged, real image of a small object placed near the lens of the lantern. This object is a series of small pictures on a flexible celluloid film (Figure 607). The pictures are taken by a special camera (Figure 608), which

automatically opens a shutter, exposes a single portion of the film, closes the shutter, and advances the film for the taking of the next picture — usually a sixteenth of a second later. When a positive of this film is passed through the projecting lantern (Figure 609), a shutter opens to permit one picture to be formed upon the screen. Then the shutter closes while the film is moved forward for the next picture, and opens for the second picture, and so on. The eye tends to retain images formed upon the retina and the pictures succeed each other so rapidly on the screen that we are not conscious of the interval between pictures when the screen is blank. *This persistence of vision* makes the moving picture appear to be continuous, whereas in reality it is a rapid succession of separate pictures. The following experiment will show



Courtesy Nicholas Power Co.

FIGURE 609. — MOTION PICTURE PROJECTOR.

The lantern at the left passes a strong light through the film. A lens just back of the rotating shutter at the extreme right forms enlarged images on the screen. One image persists in the eye until the next one replaces it.

that the projecting lantern (Figure 610) and the camera constitute a pair of optical devices, one of which serves to store up in a little space a series of small images of large

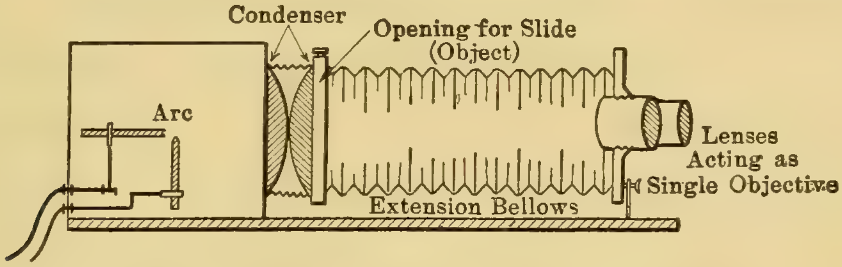


FIGURE 610. — PROJECTING LANTERN.

The condenser lenses concentrate light from the arc on the slide. The objective forms an image of the slide on the screen.

objects, and the other to form large images of these small ones. One device is the complement of the other.

EXPERIMENT 150. — Using the familiar apparatus of the last experiment, set the object candle at exactly the same distance from the lens that the image in the last experiment appeared. Move the screen as before until a clear image of the candle is formed (Figure 611). *Describe this image as to size and distance from the lens. Is the image erect or inverted? Real or virtual? How does the image distance in this case compare with the object distance in the previous experiment? Do you*

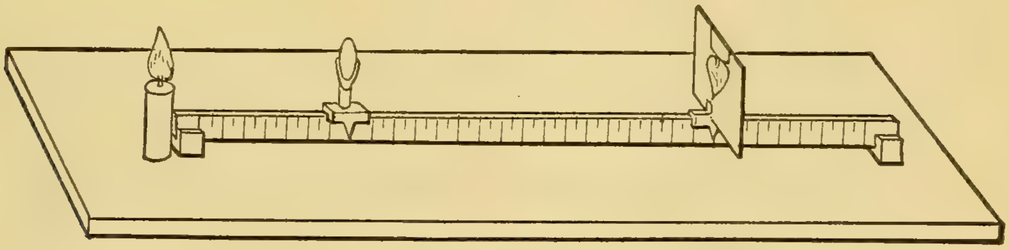


FIGURE 611. — Experimental study of one of the cases of image formation by a convex lens.

think this relation would be likely to hold good if a different object distance had been chosen in the previous experiment? Conjugate foci are a pair of points at which image and object positions are interchangeable. *How many such pairs of points may there be for a single lens?*

This experiment shows that in order to form a real, enlarged image, a convex lens must be more than the focal

length but less than two focal lengths from the object whose image is formed. Cameras used for making enlargements of small pictures follow the same practice.

420. Case IV. — Since a diminished image is formed of objects more than two focal lengths from the lens and an enlarged image results from placing the object between one and two focal lengths from the lens, we may conjecture the probable result of placing the object at exactly two focal lengths from the lens. Copying cameras form images of the same size as the object and we may learn by experiment how an object should be placed to permit a lens to form an image of the same size as the object.

Experiment 151. — Move the candle or the lens so that the distance between them is just two focal lengths. Locate the image on the screen and note its characteristics — size, distance from the lens, position, and character. *A point of two focal lengths is the dividing point between what two sizes of images? If an object is moved outside this point, what change occurs in the image? What relation exists in this case between object and image size, and object and image distance? Do you think this same relation holds good in the two former cases? In all cases?*

This experiment shows that a lens will form real images of the same size as objects placed at two focal lengths. The point located at two focal lengths is the limiting point between enlarged real images and diminished real images.

421. Case V. — The commonest use of a convex lens is as a magnifying glass or simple microscope. We know, however, that the lens used as a microscope forms images unlike the ones just discussed. Print seen through the magnifier appears right side up and enlarged. Moreover, the enlarged print seems to be on the same side of the lens as the real print is. An experiment will show how a lens may form an image so unlike the ones just studied.

EXPERIMENT 152. — Set the candle between the lens and the principal focus. Move the card as before. *Can you obtain an image on the card? Does this mean that the light is converging or diverging as it leaves the lens?* Remove the card and place your eye on the side of the lens opposite to the object candle. *Can you see an image? Describe it. Is it a real or a virtual image? If you should place a screen where the image appears to be, do you think the image would be formed on the screen?*

This experiment shows that a lens will form an enlarged virtual image of an object placed less than the focal length from the lens. Moving the candle to different positions inside the focal length will show that the greatest magnification occurs when the object is as *near* as possible to the principal focus, but the object must not be placed *at* the principal focus.

422. Case VI. — All objects placed outside the principal focus of the convex lens have been seen to be represented on the other side of the lens by real images. The last experiment has shown that a lens forms virtual images of all objects placed within the focal length of the lens. Real images are formed by the convergence of light, while virtual images result from the divergence of light. Now if you place the object candle exactly at the focal distance from the lens, you will find that you cannot obtain an image on the screen. The reason, however, that you can look through the lens and see an image of the object in this case is that one point only of the object — not all points — can be at the principal focus. The focal length of the lens is the limiting distance between object positions for real images and object positions for virtual images. The lens itself has no ability to form either kind of image of objects placed at its principal focus. Instead, it is just able to overcome the divergence of the advancing wave without being able to cause the light to converge.

Object at	Image Location	Image Size	Image Position	Image Character
1. Infinite distance	F	Small	Inverted	Real
2. Beyond $2F'$	Between F and $2F$	Small	Inverted	Real
3. $2F'$	$2F$	Same	Inverted	Real
4. Between F' and $2F'$	Beyond $2F$	Larger	Inverted	Real
5. Within F'	Beyond F'	Larger	Erect	Virtual
6. At F'	Infinity (meaning that no image is formed).			

423. General Conclusions concerning Convex Lenses. — The facts about lenses may be more easily remembered if a few general ideas are kept in mind. First: An object at a great distance from a convex lens forms an image at the principal focal length of the lens. This is the smallest and nearest image that the lens can form. Second: As the object is made to approach the lens the image recedes from the lens and becomes larger. Third: As the object reaches a point twice the focal distance from the lens, the image has receded to an equal distance from the lens and is as large as the object. Fourth: As the object is brought toward the principal focus, the image recedes to a constantly greater distance, reaching infinity when the object reaches the principal focus. Fifth: As the object is moved to less than the focal distance from the lens, the image becomes virtual and appears on the object side of the lens.

424. Construction of Lens Images. — An image of an object located at any distance from a convex lens may be constructed by drawing lines in accordance with the principles and definitions already learned. There are only two things to keep in mind in order to be able to construct any of the

lens diagrams: (1) that a ray of light parallel to the principal axis of the lens must pass through the principal focus and (2) a ray through the optical center passes through the lens

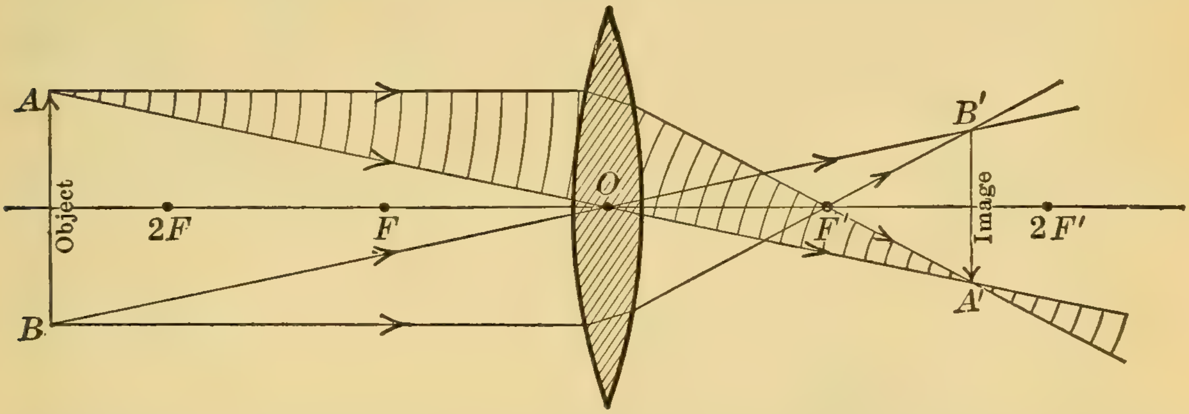


FIGURE 612. — Real image of an object more than twice the focal distance from the lens.

without deviation. Suppose that it is desired to construct the image of AB, located more than two focal lengths from the lens (Figure 612). First indicate on the figure the points $2F, F, O, F'$, and $2F'$ and draw the principal axis. From A draw a line parallel to the axis, and AO through the optical

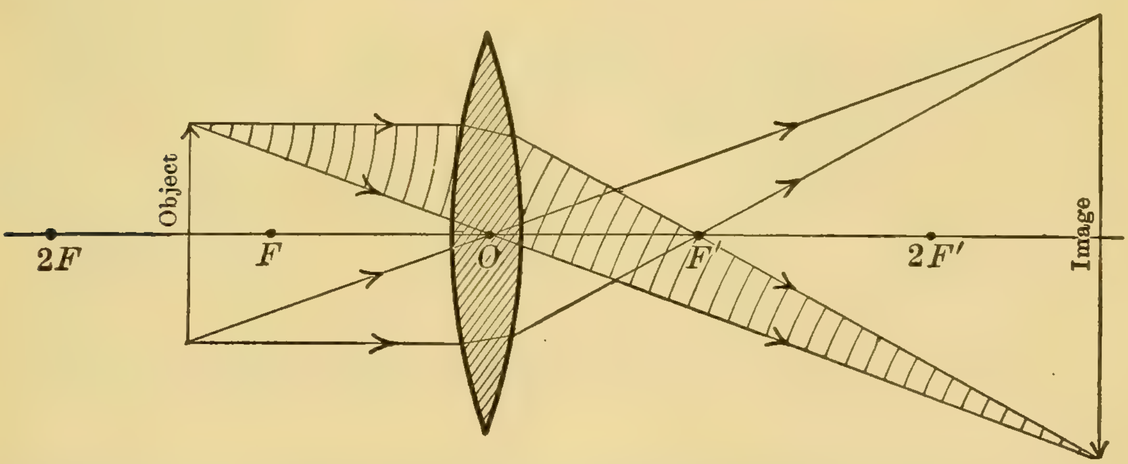


FIGURE 613. — The object is between one and two focal lengths from the lens. Compare with the preceding figure.

center. The parallel ray undergoes two refractions, one at each surface of the lens, but it must finally pass through F'. AO goes straight through the lens. The intersections of

these two rays marks the focus for all light coming from A, hence at A' a real image of A is formed. A similar construction indicates the position of B'. The diagrams for the other cases are constructed in the same way (Figures 613 and 614). Note particularly that when the object is at the principal focus, F, the rays of light leaving the lens are parallel (see Figure 603), indicating the failure of the lens to form an image. And with the object at a point inside F, the

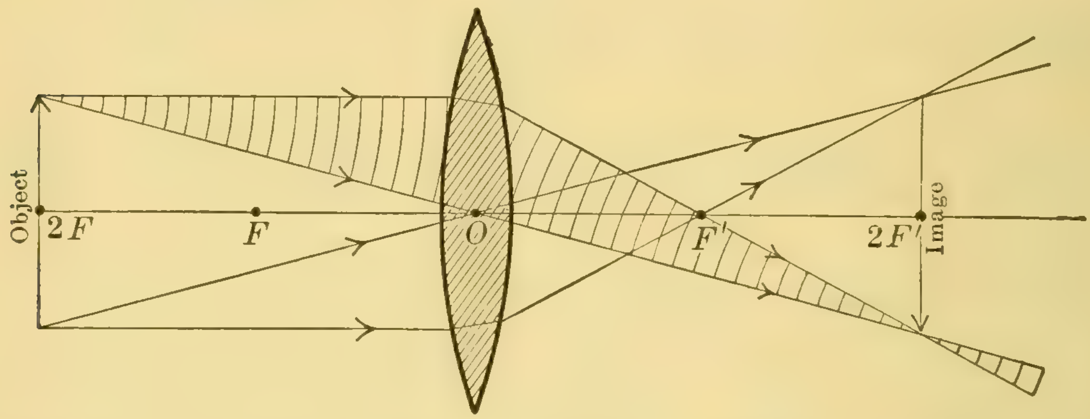


FIGURE 614. — An object at two focal lengths from the lens makes an equal, inverted image at the same distance behind the lens.

rays leaving the lens are still divergent, indicating that an *apparent* convergence is forming a virtual image on the object side of the lens (Figure 615).

425. Lens Equations. — The first lens equation is used to determine one of the three quantities — focal length, object distance, or image distance — when the two others are known. This relation is expressed by the following equation:

$$\frac{1}{\textbf{focal length}} = \frac{1}{\textbf{object distance}} + \frac{1}{\textbf{image distance}}.$$

It will appear from the diagrams (Figure 612 to Figure 615) that a convex lens gives a negative, or opposite, curvature to the wave fronts that fall upon it. The curvature of the

advancing and retreating waves becomes less as the centers of these waves become more distant from the lens — the curvature varies inversely as the distance. Finally, the curvature taken away by the lens just equals the sum of the curvatures of the waves before and after reaching the lens.

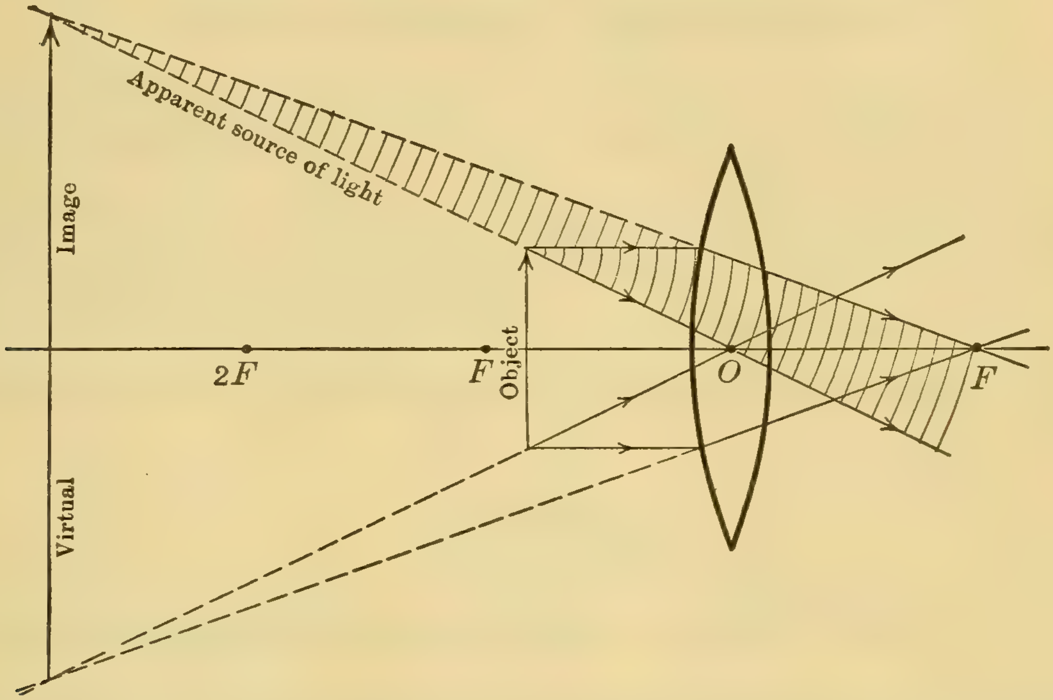


FIGURE 615. — An object within the principal focus forms an enlarged, erect, virtual image.

Application of distance equation: Where will a lens of 6-inch focus form an image of an object placed 48 inches from the lens?

Solving:

$$\frac{1}{6} = \frac{1}{48} + \frac{1}{D_i}; \; 8\,D_i = D_i + 48; \; 7\,D_i = 48; \; D_i = 6.8 \text{ in},$$

the distance of the image. Should the value of the image distance be a negative quantity, it means that the image is a virtual one; or should the image be known to be virtual, a negative quantity should be substituted in the equation for its distance from the lens.

The second equation has been foreseen in the experiments. The size of the object and that of the image are in the same ratio as their respective distances from the lens. This relation is expressed by the proportion:

$$\frac{\text{length of object}}{\text{length of image}} = \frac{\text{distance of object}}{\text{distance of image}}.$$

In this equation, lengths are compared instead of sizes, to avoid the confusion of *size* with *area*. An inspection of the construction diagrams (Figures 611 to 615) shows that the triangles AOB and $A'OB'$ are similar and therefore their bases must have the same ratio as their altitudes. Any one of these four quantities may be determined if the other three are known.

SUMMARY

A lens is a portion of a transparent substance bounded by at least one curved surface. Lenses are either diverging or converging.

Concave lenses are thinner in the center than at the edges and they **diverge** the light falling upon them. They form small, erect, virtual images.

Convex lenses are thicker in the middle than at the edges. They generally **converge** light that falls upon them and form real, inverted images, which may be of different sizes, depending upon the position of the object. See the table, page 716.

The principal focus of a convex lens is the converging point for light that falls upon the lens in paths parallel to the principal axis.

Conjugate foci are other points of focus occurring in pairs. If the object is at either conjugate focus, the image is formed at the other.

Two construction lines are necessary for **the formation of an image geometrically**: (1) a line parallel to the axis from the object to the lens, thence through the principal focus; and (2) a

line through the optical center passing through the lens without deviation. The intersection of these two lines marks the location of the image of the object.

The relation between focal length, object distance, and image distance is expressed by:

$$\frac{1}{F} = \frac{1}{D_o} + \frac{1}{D_i};$$

any one of these three quantities can be found if the other two are known.

The lengths of object and image are to each other as their respective distances from the lens:

$$\frac{L_o}{L_i} = \frac{D_o}{D_i}.$$

EXERCISES

1. Of what importance are lenses to man?

2. What sciences have been advanced by the use of lenses?

3. Name the simple forms of lenses. What is the general effect of the two main types of lenses?

4. What does a concave lens do to the light falling upon it? What kind of image does a concave lens form?

5. Explain the effect of a concave lens upon a plane wave.

6. If a wave with a curved wave front falls upon a concave lens, show what the curvature of the wave will be as it leaves the lens. Does the emergent wave appear to center nearer the lens or farther from it?

7. Does the position of the object before a concave lens determine the kind of image? Does it determine the size of image?

8. Point *A*, located above the axis of a concave lens, sends out light along the line *AD* parallel to the axis. Show by a

diagram the approximate direction of this light after it leaves the lens.

9. On a similar figure, show the path of light that reaches the lens along AO, O being the optical center of the lens.

10. Define the *principal focus* of a convex lens. Define the *focal length* of a convex lens.

11. How far from a convex lens must a screen be placed to show the image of a *distant* object? What is the appearance of the image?

12. When distant objects are being photographed, what is the approximate distance between the lens and the film of a folding pocket camera of 5-inch focal length? How should this distance be changed when nearby objects are photographed?

13. Compare the image formed by a moving-picture camera with that formed by a moving-picture projecting lantern.

14. Show by diagram the location of the image of the object AB, placed near a concave lens. Show the construction lines necessary for the location of the image and describe the image.

15. With the aid of a diagram, describe and explain the effect of a convex lens upon a plane wave falling upon the lens.

16. Two lines must be drawn from any point of an object to a convex lens to show the formation of an image of that point. What path is taken by each line?

17. On which side of the lens do these two lines intersect when a real image is formed? When a virtual image is formed?

18. At what point are plane waves, which are perpendicular to the axis of a convex lens, converged by the lens? If waves originate at this point and fall upon the lens, what will be the character of the emergent waves?

19. Describe the effect of a convex lens upon waves coming from a point located at a short distance beyond the principal focus of the lens.

20. Describe the effect of a convex lens upon waves coming to the lens from a point located within the focal length of the lens. Where do the emergent waves appear to center?

21. Define *principal focus, conjugate foci, optical center, principal axis, center of curvature.*

22. Describe an experiment by which the focal length of a convex lens can be found. Describe the image formed by the lens during the experiment.

23. At what distance from a convex lens must an object be placed in order to have the lens form an image of the same size as the object? What change will occur in the size of the image if the object is moved farther from the lens?

24. What is the least distance from a convex lens that an object may be placed and still have the lens form a real image of it? Will the image under these circumstances be large or small?

25. Describe the image formed by a convex lens placed less than its focal length from an object.

26. An arrow is placed erect and more than two focal lengths from a convex lens. Show by two construction lines the approximate position of the image of the arrow head. Sketch in the remainder of the image of the arrow to show the approximate size and position. Is the image real or virtual? Why?

27. Give your opinion as to the location and character of the image that the lens would form of an arrow having the same size and location as the image arrow in Question 26. What name should be given to the points representing the heads of the arrow and its image?

28. On a lens diagram on which you have indicated the focal points and points at twice the focal length on each side, show where the film of a motion picture should be placed in order to obtain the usual kind of picture. If the operator has to move the lens a bit farther from the film in order to focus more clearly, what change will occur in the size of the image on the screen?

29. A camera lens has a 6-inch focus. How far from the lens must the plate be in order to obtain a clear image of a person standing 12 feet from the camera?

30. A man 6 feet tall stands 10 feet from a camera lens. His image appears on the plate of the camera 6.31 inches from the lens. What is the focal length of the lens? What is the length of the image on the plate?

31. A moving-picture projector has a lens whose focal length is 6 inches. What must be the distance between the lens and the screen when the film runs at a distance of 6.1 inches from the lens?

32. What effect does persistence of vision have upon the series of pictures thrown upon the screen?

33. A reading glass has a focal length of 2.5 in. What is the greatest distance at which it can be held from the print and still form an erect image? Will the image be larger or smaller than the print?

34. The focal length of a simple microscope is 1 inch. An object is placed at a distance of 0.9 inch from the lens. Calculate the distance of the image. Is the image real or virtual? What is the relative size of image and object?

35. Find the focal length of a lens that forms an image at a distance of 4.5 inches of an object whose distance is 36 inches from the lens.

36. An object is placed 90 inches from a convex lens of 6-inch focus. Where will the image be formed?

37. An enlarging camera lens formed an image at a distance of 40 inches from the lens. If the focal length of the camera is 8 inches, where was the object placed?

38. A projecting lantern of 7.5-inch focus, forms an image on a screen 30 feet from the lens. How far from the lens must the lantern slide be placed?

39. A photographer wishes to secure the image of a 6-foot man on a 6-inch plate. If the distance from plate to lens is 8 inches, how far from the lens must the man stand?

40. In a school auditorium, the projecting lantern is 60 feet from the screen. A lecturer wishes to make pictures 12 feet square of lantern slides 3 inches square. How far must the slides be from the lens?

41. In the preceding problem, what must be the focal length of the lens?

42. A pupil experimenting with a lens finds that it will form an image at 60 cm of an object at 24 cm. What is the focal length of the lens?

43. When the object in the preceding problem is moved to a distance of 48 cm, where will the image be and how large will the image be if the object is 5 cm tall?

44. An object is placed 2 inches from a lens of 2.5 inch focal length. Where will the image be? (Note: A – quantity indicates a virtual image.)

CHAPTER XXXII

OPTICAL INSTRUMENTS

426. The Eye. — The eye is the most interesting and important optical device (Figure 616). It may be simply described by comparing it with a camera, since it consists of a chamber into which light is admitted through a small opening, the *pupil*, to be focused by a convex lens upon a sensi-

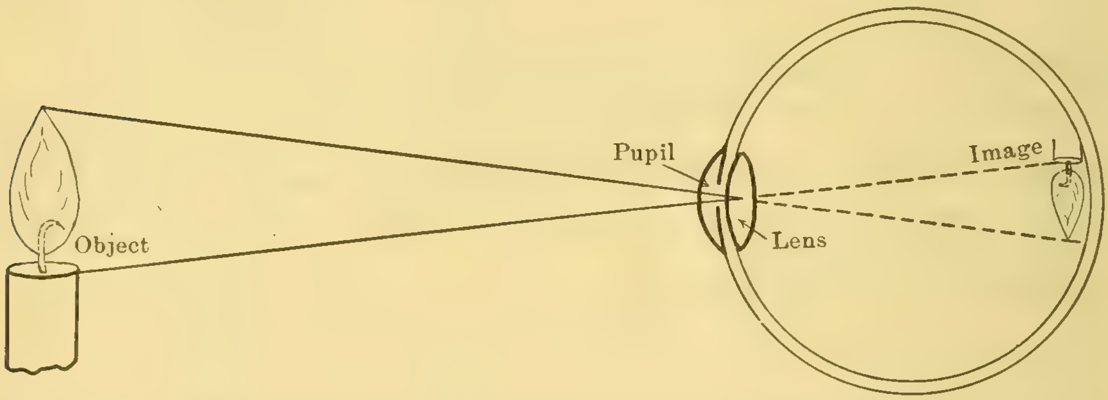


FIGURE 616. — The eye is a miniature camera forming on its retina images of objects around us.

tive screen, the *retina*, at the back of the eyeball. The colored portion (iris) of the eye is an adjustable diaphragm, which regulates automatically the amount of light entering the eye. With an ordinary lens, the image distance must change every time the object distance changes. In the eye, however, the distance of lens to image is practically constant, being the depth of the eyeball. Objects at different distances are focused upon the retina by the automatic changing of the convexity of the lens by muscular action. At the same time, perhaps, some change takes place in the depth of

the eyeball itself. When objects are brought close to the eye, the light from them is widely divergent as it reaches the eye. To overcome this divergence and focus the light upon the retina, the muscles that adapt the eye increase the thickness or convexity of the lens so that the image still falls upon the retina. For distant objects the lens becomes less convex, that is, relatively thinner in the middle so that the image can be brought upon the retina. The eye loses this power of *accommodation* somewhat as the person becomes older. It is evident from previous paragraphs that the real image upon the retina is inverted. The question of why we see things erect is one for psychology rather than for physics, but it is probable that experience acquired in infancy helps us to form an opinion as to where things really are, and then to think that we see them so. The judgment as to the proper size of objects is obtained in like manner, since to the eye a man 10 feet distant appears 5 times as large as a man at 50 feet.

In order to have a standard for measurement, the distance for clearest vision is arbitrarily taken as 10 inches. Eyes are tested, spectacles are adjusted, and the magnifying power of lenses is determined by reference to this standard. Farsighted persons see most clearly at distances greater than 10 inches or lose their power of accommodation for nearby objects. Nearsighted persons bring objects within this distance in order to secure clear vision. The farsighted person, having a lens that is chronically too thin in the middle, or an eyeball too short (Figure 617 bottom), obtains relief from his trouble in reading by wearing convex lenses to aid his eyes. Conversely, the nearsighted person, with a lens chronically too thick at the middle for the depth of his eyeball (Figure 617 middle), is able to see distant objects

clearly by wearing concave lenses to take away some of the converging power of his eye lenses. The third common defect of vision is astigmatism, which is due to the lens of the eye having a different curvature in some planes than in others. This defect is relieved by the use of glasses that are convex in the plane where the eye is concave and vice versa. Common defects of the eye are easily discovered and remedied by glasses, so that such defects should not go untreated.

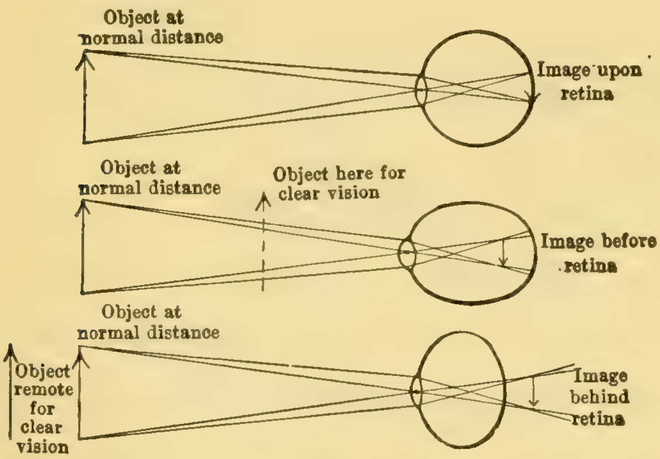


FIGURE 617. — Top: Normal vision, lens thickness correct for depth of eyeball.
Center: Nearsightedness, lens too thick, or eyeball too deep, or both.
Bottom: Farsightedness, lens too thin, or eyeball too shallow, or both.

427. Defects of Other Lenses. — Theoretically, it would appear that all light that reaches a lens along a path parallel to its principal axis should converge at the principal focus of the lens. Actually, the light fails to be focused at a single point. The light falling upon the edges of the lens converges at a point nearer to the lens than that which falls upon the middle (Figure 618). This unequal focusing by the lens is known as *spherical aberration*. In a camera, light is excluded from the outer portions of the lens by a diaphragm, to avoid spherical aberration.

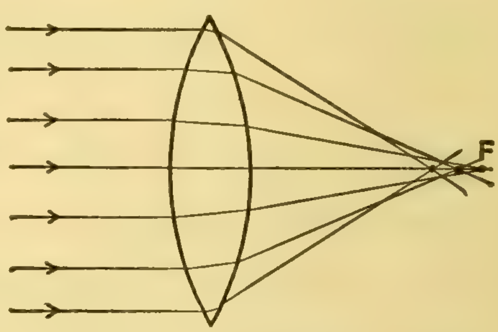


FIGURE 618. — SPHERICAL ABERRATION.

The edges of an ordinary convex lens focus light nearer than the middle does.

428. Chromatic Aberration. — The different refraction of the various wave lengths of light is the basis of the dispersion of light. The waves corresponding to red are bent less than those corresponding to violet, with the others as intermediates between these two. A simple lens must always form an image with a colored fringe (Figure 619, *A*). Newton did not know of the different refracting power of various kinds of glass and therefore thought that in all

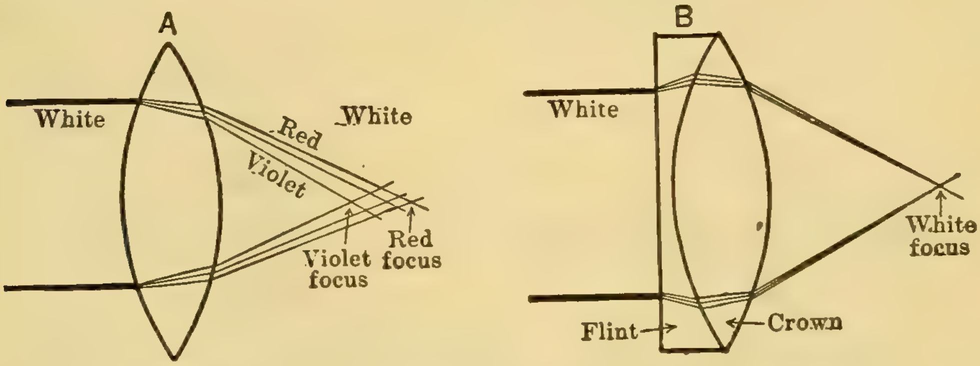


FIGURE 619. — CHROMATIC ABERRATION.

Different wave lengths are focused at different distances by the ordinary lens (*A*). This *chromatic* aberration is corrected by the combination lens (*B*).

images the red would focus at one place far from the lens with the other colors in order nearer the lens. The telescope and the compound microscope were both at a standstill in development because of this defect. Soon after Newton it was discovered that a convex lens of crown glass combined with a concave lens of flint glass would cure the dispersion but still cause refraction (Figure 619, *B*). All good lenses for optical instruments are now constructed on this plan. Since other corrections must also be made, the modern lens is very often a complicated affair of many parts, either separate or fastened together.

429. Optical Instruments. — The use of lenses in the camera and in the simple microscope has already been discussed. The compound microscope consists of two sets of

lenses, one called the *eyepiece,* the other the *objective.* The objective is a short focus lens placed a little more than its focal length from the object to be examined. Under these conditions, it forms a distant, large, real image in the cylinder of the instrument. The eyepiece is a short focus lens placed so that the image formed by the objective lies just within the eyepiece focus. Thus the eye sees with the eyepiece an enlarged virtual image of the enlarged real image formed by the objective (Figure 620). Since light from a very small object is spread over a large area, the image be-

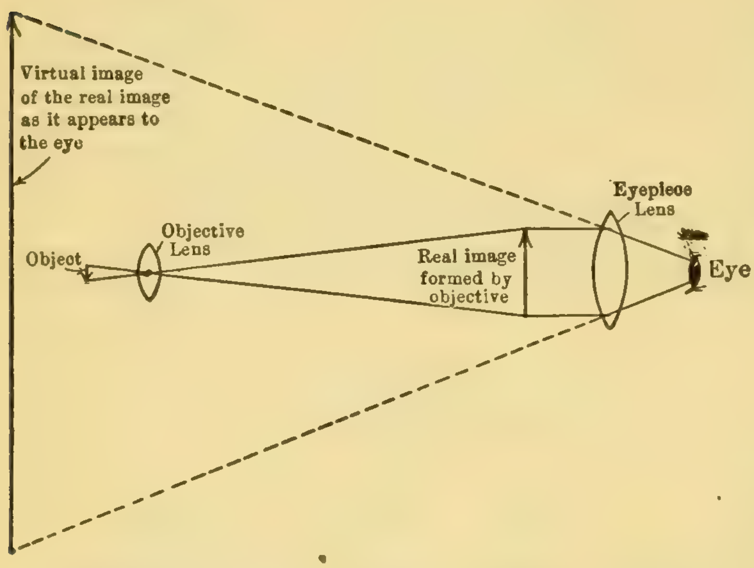


FIGURE 620. — COMPOUND MICROSCOPE.

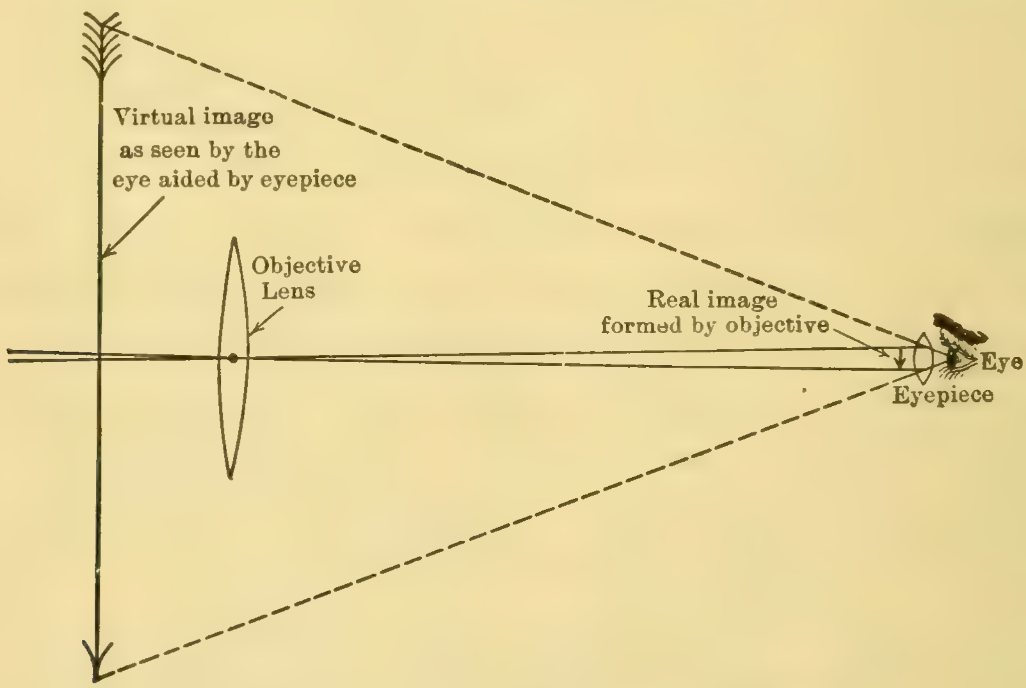


FIGURE 621. — ASTRONOMICAL TELESCOPE.

The image is inverted.

comes dimmer as the magnification increases. The limit of magnification is reached as the image becomes too dim to be seen.

The *astronomical telescope* (Figure 621) is very similar to the compound microscope, except that a lens of long focus is used for an objective. This lens is also of great diameter, so that more light will fall upon it. The stars, being points of light due to their great distance from us, are not magnified by this telescope but are brought nearer. Both the telescope and the compound microscope form inverted images.

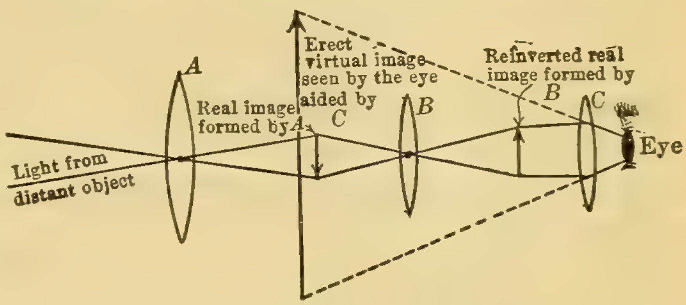


FIGURE 622. — TERRESTRIAL TELESCOPE. The third lens, *B*, reinverts the image.

The *terrestrial telescope* (spyglass) is a combination of a simple lens with a compound microscope. The simple lens forms a real inverted image, which is examined by the microscope. The microscope reinverts the image, thus making it appear upright (Figure 622), and further magnifies it.

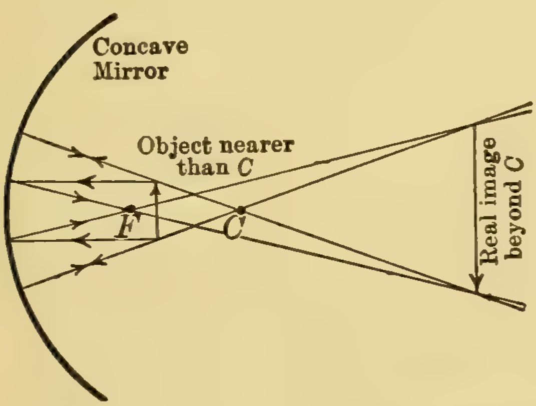


FIGURE 623. — Concave mirrors form real, enlarged images of objects within the center of curvature.

Opera glasses have a concave eyepiece which neutralizes the convexity of the eye. A convex objective then forms an image on the retina. Because this image distance is greater, the size of the image is correspondingly greater. The magnification produced by these glasses is usually from two to six diameters. Field glasses and

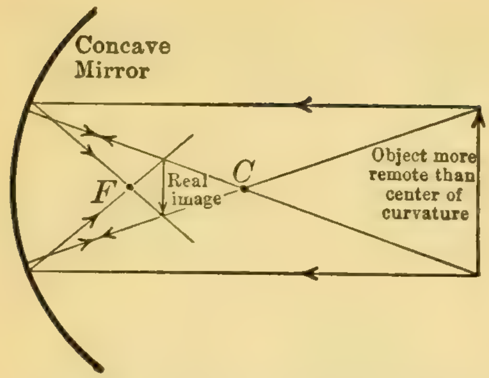


FIGURE 624. — Concave mirrors form real, diminished images of objects outside the center of curvature.

telescopes producing a greater magnification need a fixed support to keep one part of the field constantly in view.

430. Spherical Mirrors. — The effect of curved mirrors upon light has been mentioned in § 182. This effect can be briefly described by saying that concave mirrors produce a series of images like that of the convex lens, while the convex mirror produces a virtual image as the concave lens does. The real images formed by the mirror are on the same side of the mirror as the object, while the virtual images formed are behind the mirror. The principal focus of the mirror is located at half its radius, while the principal focus of the lens depends for its position upon the shape of the lens and the refracting power of the kind of glass used in its construction, a double convex lens of ordinary glass having its principal focus about at its center of curvature. The construction diagrams for the various mirror cases are all made in the same way (Figure 623 to Figure 626): a ray parallel to the principal axis is reflected according to the law of reflection through the principal

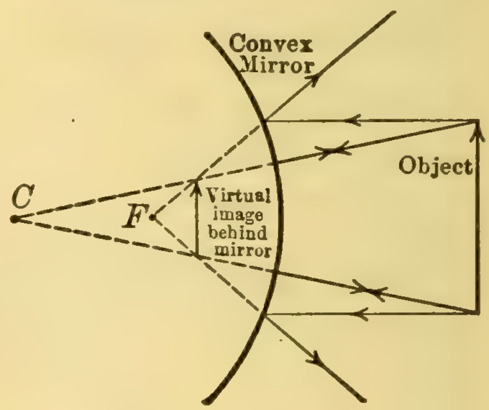


FIGURE 625. — Convex mirrors form small virtual images.

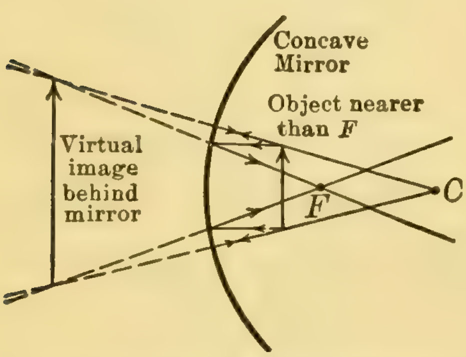


FIGURE 626. — Concave mirrors form virtual images of objects within the principal focus.

focus, while a second ray through the center of curvature is reflected back along its path since it is normal to the mirror. The intersection of these two reflected rays is likewise the intersection of all reflected light emitted by one point of the object and is therefore the image of that point. An intersection that occurs behind the mirror indicates a virtual image.

Since the concave mirror is not troubled by chromatic aberration, it is used at times for the objective of telescopes. The light, instead of being formed into an image by a lens, is reflected into the cylinder of the telescope. An inclined plane mirror permits the image to be seen through an eyepiece which is at right angles to the axis of the telescope (Figure 275, page 210).

The relation between the principal and conjugate foci of curved mirrors is expressed by the same equation as that used for lenses:

$$\frac{1}{F} = \frac{1}{D_o} + \frac{1}{D_i}.$$

SUMMARY

The **eye** possesses a compound lens, which forms real, inverted, diminished images upon the retina. It accommodates itself to various object positions by muscular control of the thickness of the lens and of the depth of the eyeball.

Spheric aberration results from the failure of glass lenses to focus all the light from one point of an object at a single focus. **Because of chromatic aberration**, different wave lengths are refracted unequally and do not converge at the same point of focus. This kind of aberration can be corrected by an achromatic lens, formed of two kinds of glass.

Concave mirrors form a series of images like those of the convex lens. **Convex mirror** images are like those of the concave lens.

EXERCISES

1. Name the parts of the eye. State the use of each part.

2. Where is the eye lens? How does it accommodate itself to varying object positions? Is this accommodation voluntary? Instantaneous?

3. Where are the eye images formed? Describe them. How do you think we obtain correct ideas as to size and position of things?

4. What is the reason for nearsightedness? What kind of lens relieves it? What kind of lens is used for farsightedness?

5. Describe spheric aberration by aid of a diagram. Why do large telescopes focus light with a concave mirror instead of a convex lens?

6. What is chromatic aberration? Make a diagram of a lens in which it is corrected.

7. Compare astronomical telescope images with field glass images. What causes the difference?

8. What is the difference in construction between a simple and a compound microscope? What is the difference in their images?

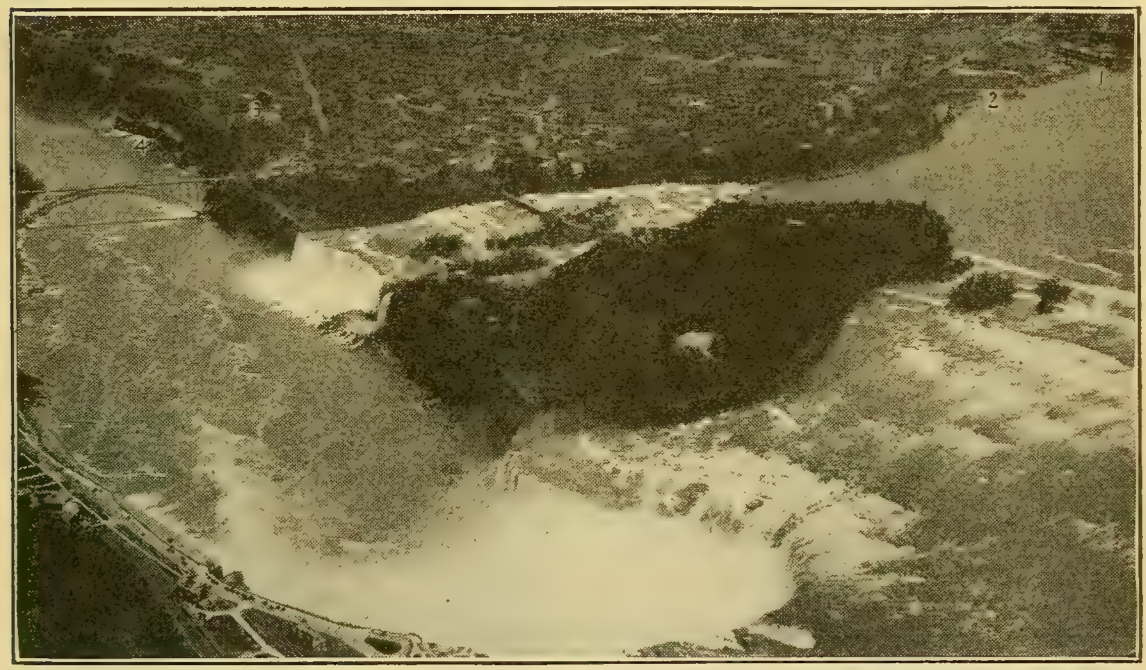
9. Compare lenses and spherical mirrors as to the kind of images formed. On which side of a concave mirror is its real image formed?

10. Construct the image of an object placed at two focal lengths from a concave mirror. At four focal lengths. At less than one.

CHAPTER XXXIII

WATER POWER

The use of running or falling water as a source of power was, after the use of the wind for sails, probably man's first attempt to utilize natural energy to do his work. The rather crude and inefficient water wheels of early days were largely



Courtesy Niagara Falls Power Co. © Ronne and Washburn.

FIGURE 627.—NIAGARA FALLS FROM AN AIRPLANE.

Water taken from the upper river at 2 is utilized by the power plant at 4.

discarded when the steam and internal-combustion engines were developed. The invention of the turbine and impulse wheel, together with increasing cost and scarcity of fuel, has served to make water power of importance again, and one of the foremost engineering questions of the day.

431. Water Pressure. — We have already discussed water pressure (Chapter III), both that due to the weight of the water and that caused by some external force, such as that of a pump piston, and transmitted unchanged by the water. Transmitted pressure, caused by a pump, is used only in the operation of small domestic water motors, and for elevators and similar hydraulic machinery. In all water-power installations, we depend on the potential energy of an elevated body of water. This potential energy is the result of the work done by the sun in cloud formation by evaporation from oceans and lakes.

432. How Water Does Work. — Both the weight of the water and its kinetic energy due to motion are utilized in water-power machinery. In every case, the main source of water supply must be at a higher level than the wheel that uses it. If the water level in the supply is 50 feet higher than the point at which it leaves the water wheel, we say that the water is supplied under a " head " of 50 feet. The greater the head, the greater will be both the gravity pressure due to the water and the speed with which it flows through the wheel.

No matter by what path the water is conveyed from the reservoir or headwaters to the water wheel, the pressure at the wheel depends only on the vertical height of the reservoir level above the wheel. Unless the fall is direct and uninterrupted, not all of this head is practically available, since some of the pressure is used up in overcoming friction in pipes and eddies caused by bends. As the pressure is present whether the water is flowing or not, penstocks, gates, and wheel casings must be made strong enough to withstand the pressure.

From what has been said regarding pressure, it will be

seen that it is best to install water-power plants at natural or artificial water falls, and particularly in mountainous regions. As water wheels are especially adapted to operate electrical generators, electrical power generated at inaccessible points may be used to run railroads or be transmitted to towns and cities, where it may be conveniently utilized. Hence nearly all modern water-power developments are hydro-electric plants.

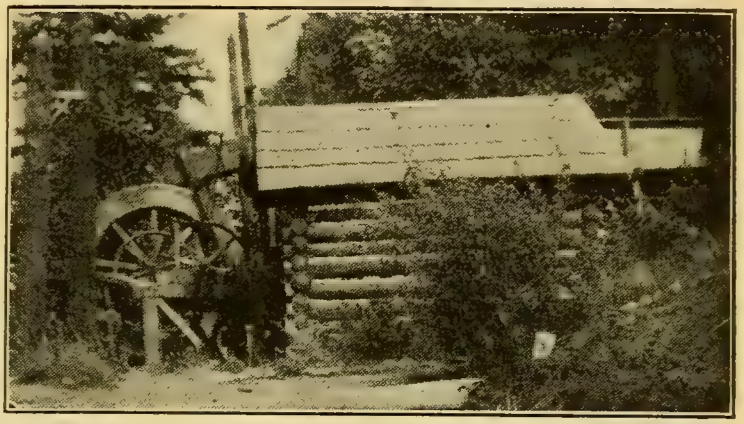


FIGURE 628. — AN OVERSHOT WHEEL.

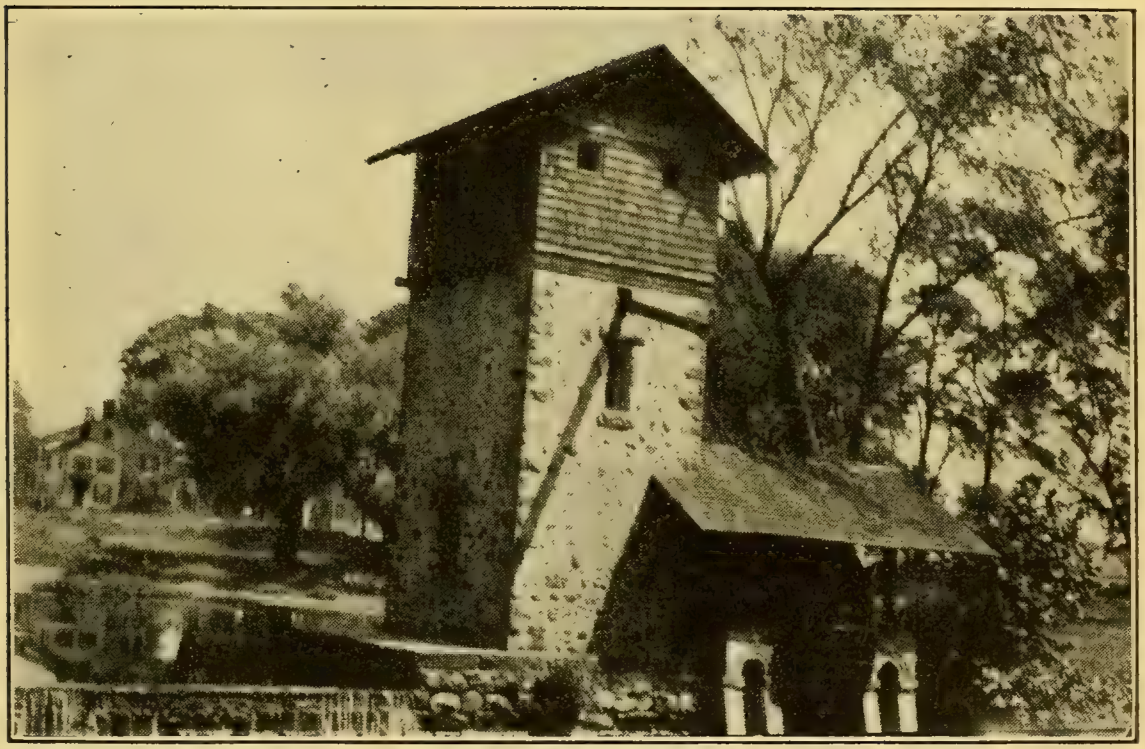


FIGURE 629. — AN UNDERSHOT WHEEL.

433. Primitive Water Wheels. — Early forms of water wheels include overshot, undershot, and breast wheels. The overshot wheel (Figure 628) is a large vertical wheel having

the space near the rim divided into *buckets* by wooden or curved iron partitions. The water falls from a trough into these buckets near the top of the wheel, and both the weight of the water and the force due to its velocity unite to turn the wheel. To secure any considerable power from such a wheel, it must be large. Overshot wheels are adapted to locations where relatively small amounts of water can fall on a high wheel. They have been made over 70 feet in diameter and may have an efficiency as high as 80%. They are bulky and cumbersome, however, and cannot be used for the development of large amounts of power.

FIGURE 630. — OLD BREAST WHEEL AT WARWICK, ENGLAND.

Where there is little fall to a stream, but an abundance of water, undershot wheels have been employed (Figure 629). These were constructed like the paddle wheel of a steamer, and depended on the force of the current to turn them. Their

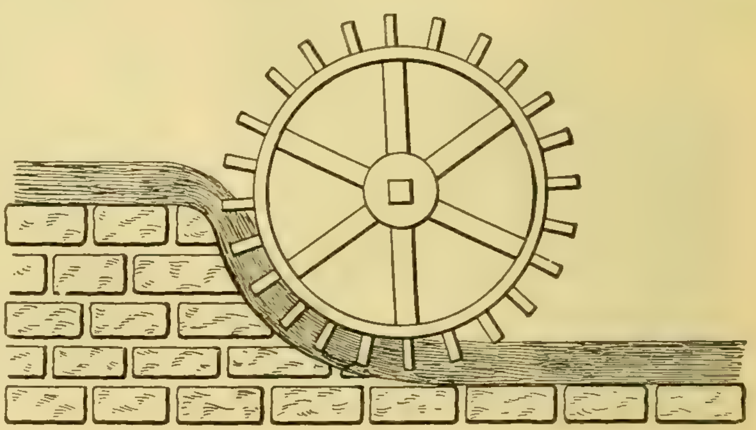
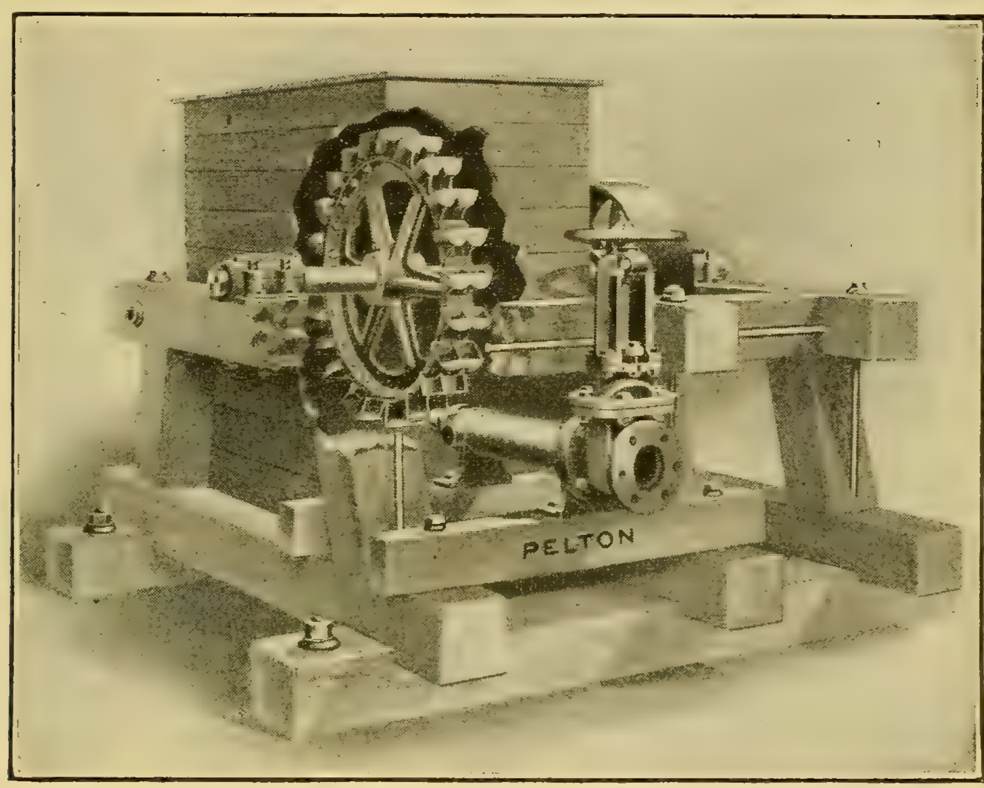


FIGURE 631. — The breast wheel uses both the weight and the kinetic energy of the water.

efficiency was very low. A somewhat more efficient wheel was the breast wheel (Figure 630). The picture shows that the stream has been dammed to raise the level a few feet, and the water is admitted at about the level of the axle of the wheel. A curved trough in which the wheel turns keeps the buckets full (Figure 631) and so the wheel utilizes both the weight of the water and the force of the stream.



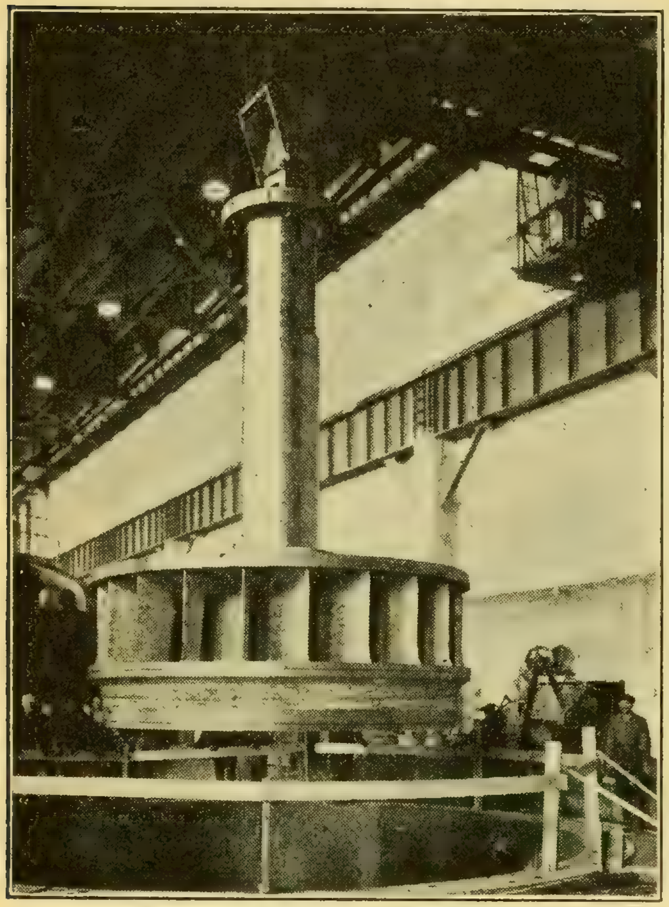
Courtesy Pelton Water Wheel Co.

FIGURE 632. — IMPULSE WHEEL.

The curved buckets receive the force of the water from the nozzle in the foreground. The reaction as it leaves the buckets gives added power.

434. Impulse Wheels. — When water in a hose or pipe is delivered under pressure through a nozzle, a stream of great velocity and kinetic energy results. This is illustrated in battering down the walls of a burning building by the stream from a fire hose. If water from a mountain reservoir or other high head source is directed through a nozzle against buckets set on the circumference of a steel wheel (Figure 632), a small

jet of water under great pressure will develop a great deal of power in a small wheel. Such a water wheel is called an *impulse* or *Pelton wheel.* These are widely used in the western mountain region, where heads of hundreds of feet are available. Small water motors for domestic use utilize city water pressure in much the same way.



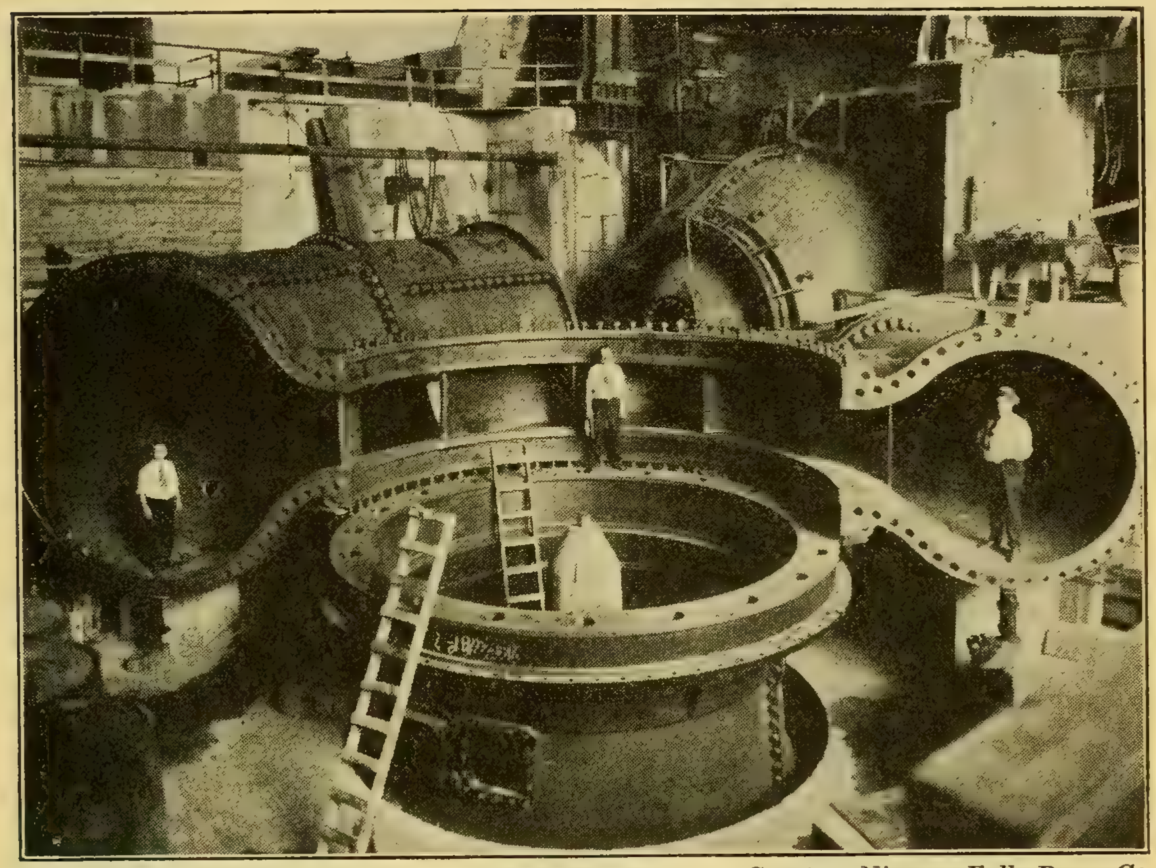
Courtesy Niagara Falls Power Co.

FIGURE 633. — Runner of 70,000 h.p. Turbine at Niagara. It is being lowered into the casing shown in the next picture.

435. Turbines. — The most common type of modern water wheel is the turbine. This may be designed for high heads of 150 to 300 feet, as at Niagara Falls, or for low heads with great volumes, as on the Mississippi and St. Lawrence Rivers. Turbines vary in construction, but the essential parts of all are the same. These are: (1) the turbine proper, or *runner*, consisting of a wheel with curved blades or *vanes* (Figure 633); (2) the *inner casing,* which is stationary and contains oppositely curved *guide vanes,* which direct the water against the vanes of the runner (Figure 634); and (3) the *outer casing,* which completely incloses the other two parts and forms the end of a vertical or inclined pipe or *penstock* that conveys the water to the wheel from the intake above. The gravity pressure of the water causes it to flow in between

the guide vanes against the vanes of the runner and forces the runner to turn. The runner vanes are so designed that the water can escape after turning the wheel.

When the guides surround the runner, the latter discharges through its center and the turbine is called an *inward-flow*



Courtesy Niagara Falls Power Co.

FIGURE 634. — INNER AND OUTER CASINGS AT NIAGARA.

The man in the center is standing in front of one of the guide vanes of the inner casing, and the other men are in the outer casing. The end of the penstock and the valve are seen at the rear.

turbine. In *outward-flow turbines,* the runner vanes are set in a ring that rotates around stationary guides, which receive the water from the penstock at the center of the wheel. The *mixed-flow turbine,* shown in Figure 635, receives the water into the upper part of the wheel through surrounding guides, and discharges it in an outward direction at the bottom, thus utilizing the reaction of the water.

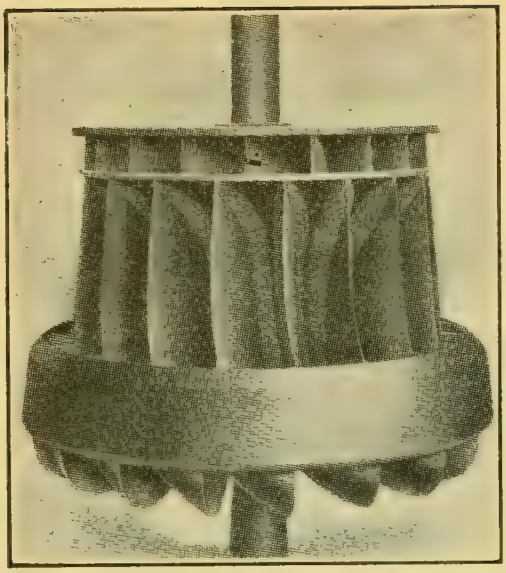
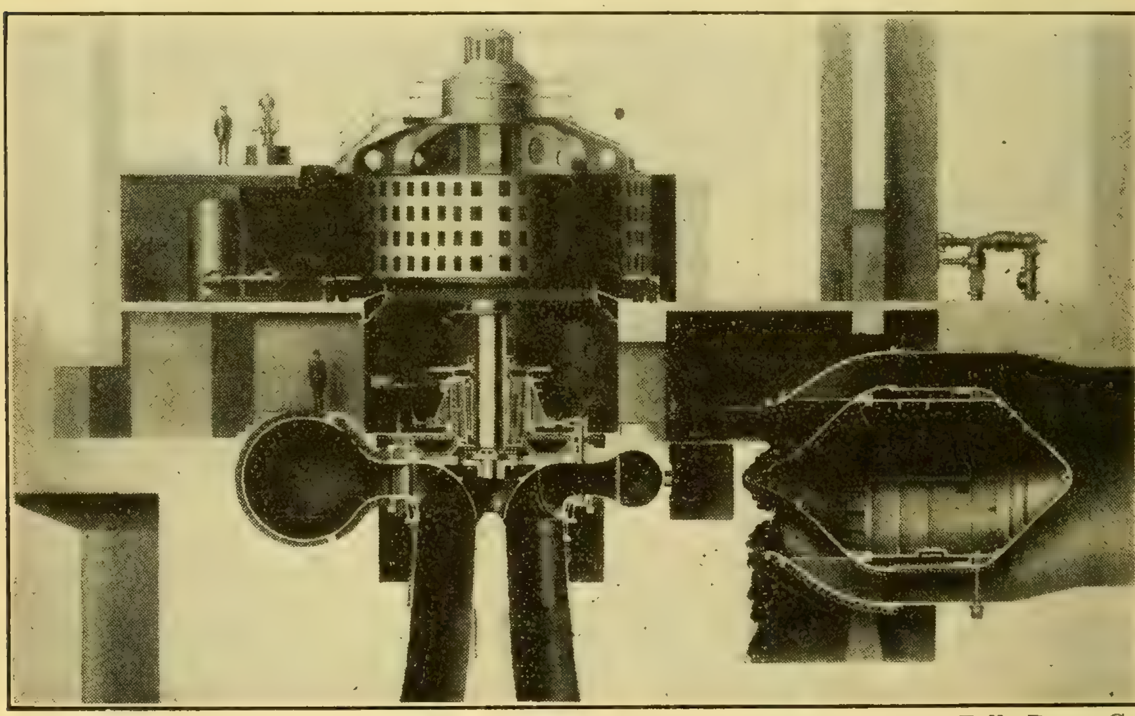


FIGURE 635.—RUNNER OF MIXED FLOW TURBINE.

Turbines may be mounted so that the runner is either horizontal or vertical. In either case, the shaft of the runner is connected directly or through reducing gears to the shaft of the generator or other machine to be driven (Figure 636). The flow of water to the turbine is governed by increasing or diminishing the opening between the guides. Large turbines show an efficiency often considerably in excess of 90%, and the range of size is from a few horse power to over 70,000 horse power.

436. Niagara Falls Plants. — In the most modern developments on both the American and Canadian sides of the

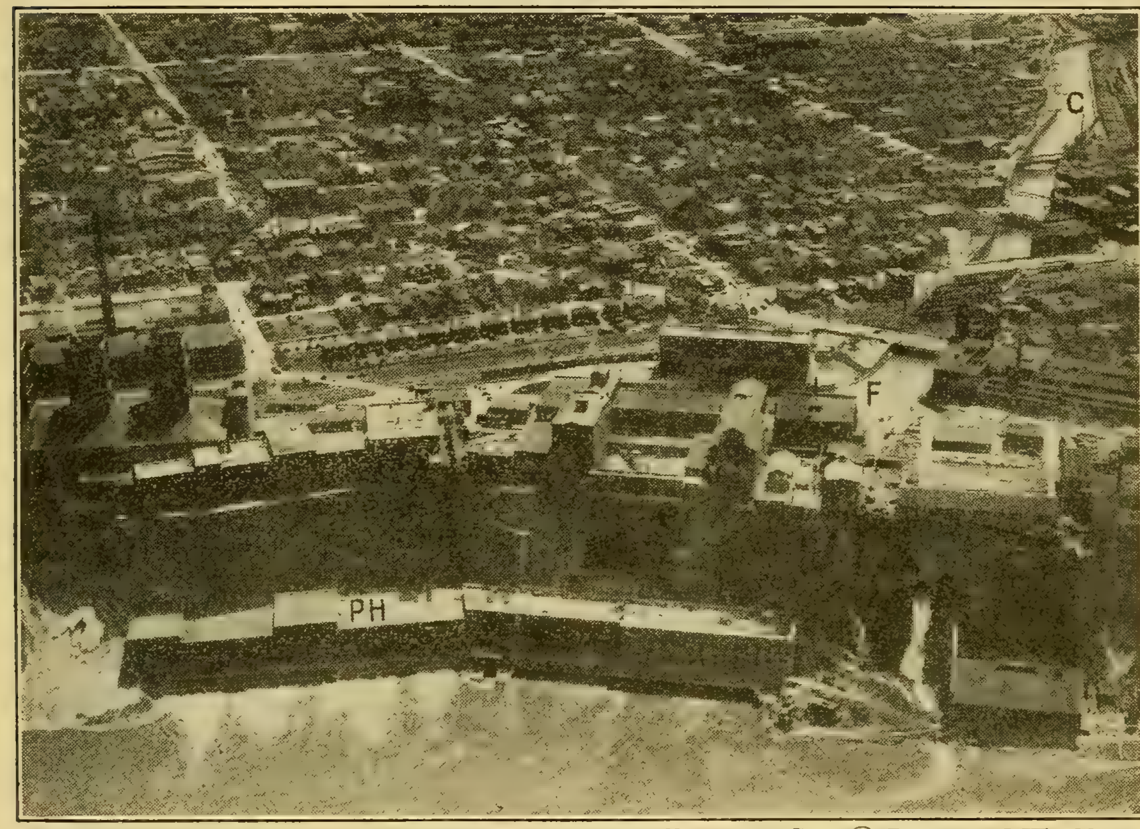


Courtesy Niagara Falls Power Co.

FIGURE 636. — NIAGARA INSTALLATION COMPLETE.

Water from the penstock at the right flows through the casing and runner, and discharges downward through a draft tube. The generator is mounted above on the turbine shaft.

Niagara River, the water is diverted from the river at points above the rapids and falls, and conveyed through open cuts (*C*, Figure 637) or through large tunnels to basins or *forebays* (*F*) at the top of the bank some distance below the falls. From the forebay, large steel pipes or *penstocks* lead down to



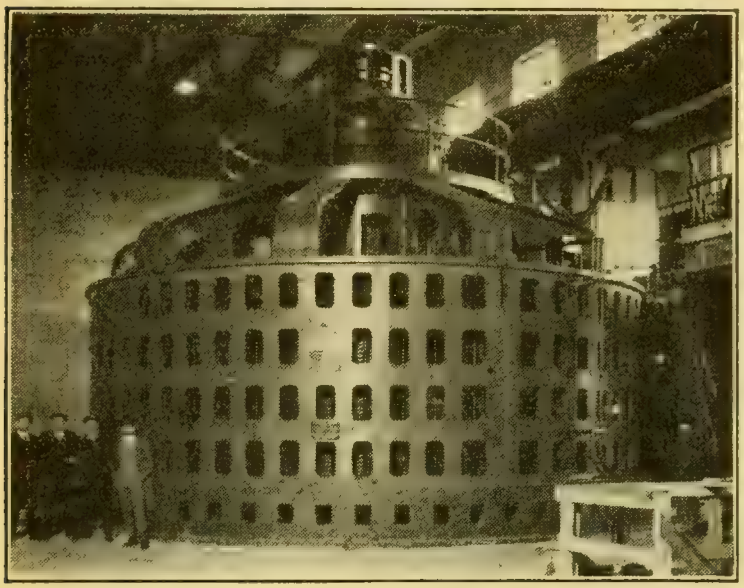
Courtesy Niagara Falls Power Co. © Ronne and Washburn.

FIGURE 637. — NIAGARA FALLS POWER COMPANY, AIRPLANE VIEW.

Part of the water flows through the canal (*C*) and part through a huge tunnel. Both open into the forebay (*F*), from which the water is carried in penstocks to the turbines in the power house (*PH*). The discharge from the wheels can be seen coming out below the power house.

the power house (*PH*), which is built at the foot of the bank, just above the level of the lower river. After passing through the wheels, the water flows out under the power house into the river. The generators (Figure 638) are mounted above the wheels. The sectional drawing (Figure 639) shows clearly the relation of the parts of the system. Three of the turbines are the largest in the world, developing 70,000

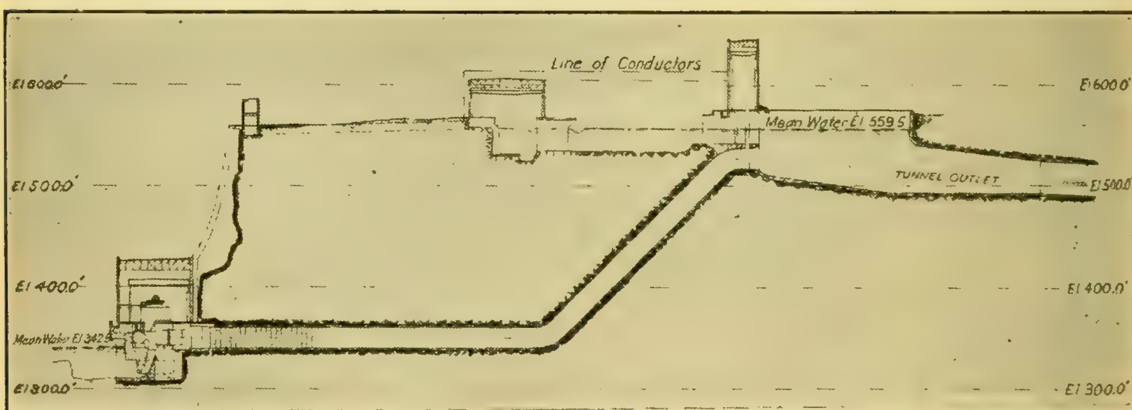
horse power each, under a head of 215 feet. The total capacity of the Niagara Falls Power Company's American Plant is 450,000 horse power.



Courtesy Niagara Falls Power Co.

FIGURE 638. — GENERATOR DRIVEN BY ONE OF THE 70,000 H.P. TURBINES AT NIAGARA.

437. Water Currents. — Water flows only when there is a difference of pressure. In streams, the bed slopes more or less rapidly from the headwaters to the mouth. We commonly rate the current in a stream in miles per hour, the rate at which a floating body is borne along. When the water is to do work, however, we measure the current in gallons per minute or in cubic feet per minute. Evidently this current will depend on both the pressure and

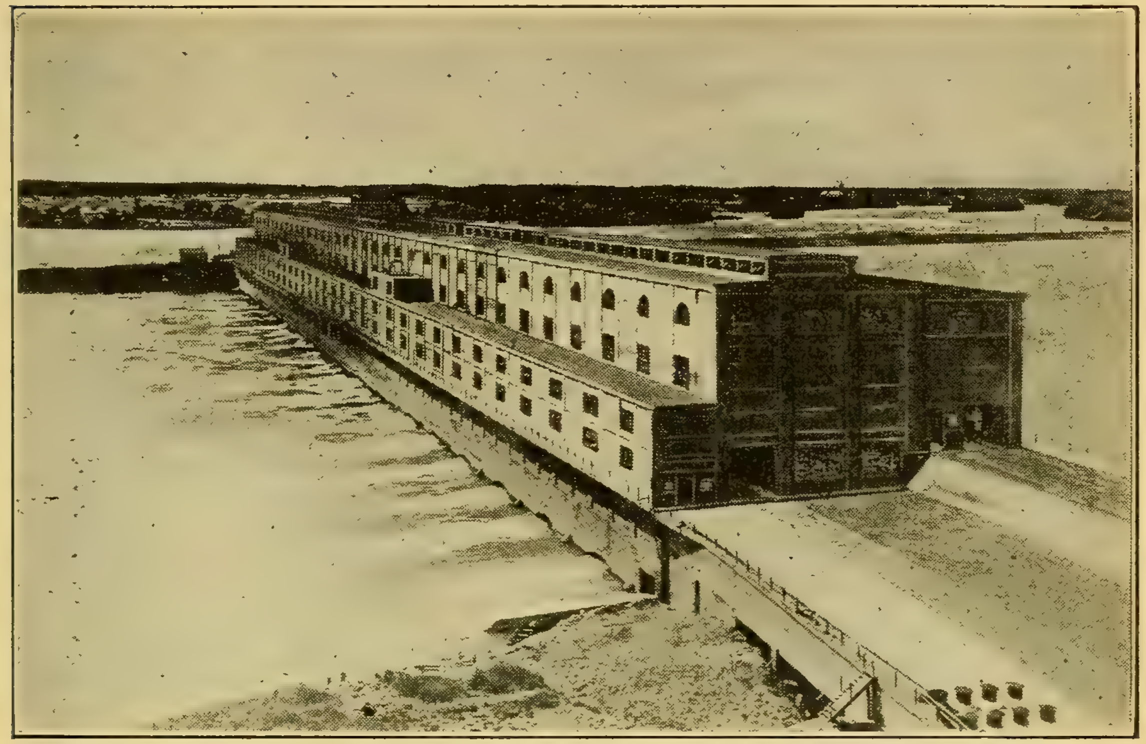


Courtesy Niagara Falls Power Co.

FIGURE 639. — SECTIONAL VIEW, SHOWING (RIGHT TO LEFT) TUNNEL FOREBAY, AND POWER HOUSE.

the size of the pipe, just as an electric current depends on the difference in pressure and the resistance of the conductor.

438. Water Power. — A large stream of water, with a high head, will evidently do more work per minute — have greater power — than the same stream with a smaller head, or a smaller stream with the same head. Since a cubic foot of water weighs 62.5 lbs, we calculate the work per minute



Courtesy Montreal Light, Heat, and Power.

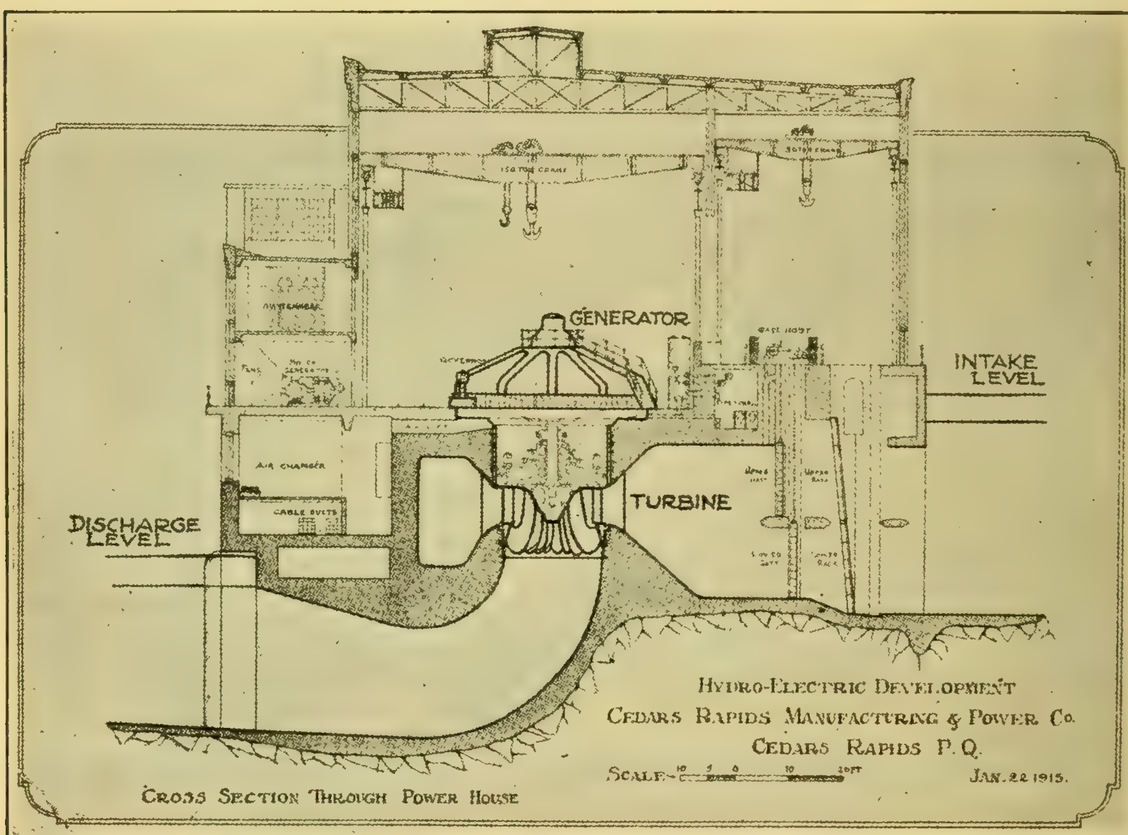
FIGURE 640. — CEDARS RAPIDS POWER HOUSE, SHOWING INTAKE CHANNEL BEHIND AND DISCHARGE FROM THE WHEELS AT LEFT.

that is done on a water wheel by multiplying together the head in feet, the cubic feet per minute, and 62.5. Dividing this product by 33,000, we have the horse power applied.

$$\text{Horse power} = \frac{\text{ft head} \times \text{ft}^3 \text{ of water per minute} \times 62.5}{33{,}000}$$

As pointed out above, not all of this power is actually available at the wheel, since some is used up in pipes and penstocks. This loss, however, is small in well-designed plants, hence the efficiency of turbines and impulse wheels is high.

439. Low-head Installation. — As typical of situations where a large volume of water at a low head is available, the installation at Cedars Rapids, Canada, may be briefly described. At this point the level of the St. Lawrence falls about 30 feet in less than a quarter of a mile through a series of rapids. A dyke, parallel to the river bank, was constructed



Courtesy Montreal Light, Heat, and Power.

FIGURE 641. — SECTIONAL VIEW OF CEDARS RAPIDS PLANT.

These low-head, mixed-flow turbines take 3700 cubic feet of water per second to generate 11,000 horse power.

in the river bed. At the lower end this was connected to the bank by a dam, to concentrate the pressure of the water on the water wheels. The dam forms the foundation of the power house (Figure 640), the wheels being set in the dam itself. The wheels are of the vertical type, and their runners are set half way between the upper and lower levels of the water. By connecting the discharge of the

wheel by means of a *draft tube* of proper design with the tailrace, which carries the water to the river, the total pressure of the water on the runner is the same as if the wheel discharged directly at the level of the tailrace. The effect of the column of water in the draft tube is to exert a pull on the runner equivalent to the weight of a column of water of the same height, above the wheel. By the use of draft tubes, troubles due to ice and to changes in the river level are avoided, and draft tubes are used in all turbine installations.

The generators are set directly on the water wheels (Figure 641). Each wheel, taking 3700 cubic feet of water from the canal per second, and making 56 revolutions per minute, develops about 11,000 horse power at the generator, in spite of the fact that the available head is only about 30 feet. The horizontal generators are less than 3 feet high, but the rotating part is 32 feet in diameter. The power is transformed and distributed in the usual way.

SUMMARY

Water does work when it falls from a higher to a lower level, both by its weight and by its kinetic energy. **The head of water** is the vertical distance from the upper level to the point where it is utilized.

Overshot water wheels depend on the weight of the water in the buckets on the circumference of the wheel. **Undershot** wheels depend on the kinetic energy of the water in the stream in which they are placed. **Breast** wheels take the water at the level of the axis and utilize both weight and kinetic energy. These forms of wheel are now little used.

The impulse wheel is turned by water directed through a nozzle against buckets on the rim. These wheels are used in mountainous regions, where the head is great and the volume of water relatively small. Small water motors are usually of this type.

Turbines are the most common type of modern wheel. The water is directed through curved passages of the casing against curved blades of the runner. The flow may be either inward or outward, and the wheels may be either vertical or horizontal. Turbines depend on the gravity pressure of the water.

The power developed by water wheels is

$$\text{Horse power} = \frac{\text{ft head} \times \text{ft}^3 \text{ per min} \times 62.5}{33{,}000}$$

The energy developed by water power is chiefly utilized for generating electrical power.

EXERCISES

1. Why is an elevated supply of water necessary for the development of water power?

2. What is the *head* of water, and in what units is it measured?

3. Explain the use of dams in water-power projects.

4. Why are power houses frequently located near waterfalls?

5. Make outline drawings of three forms of primitive water wheels.

6. Describe how the water acts in each of these wheels.

7. Describe the construction and action of an impulse wheel.

8. Under what conditions are these wheels used?

9. Name the three parts of a turbine wheel and describe the use of each part in the operation of the wheel.

10. What is a *penstock?*

11. Explain the difference between inward, outward, and mixed-flow turbines.

12. Show how both potential and kinetic energy are utilized in water wheels.

13. In what two ways may water currents be rated? Which is more important in water power?

14. What are the factors that determine the amount of power to be developed by water?

15. One of the Niagara turbines uses 17,200 ft^3 of water per minute under a head of 215 ft. What is the horse power developed?

16. What would be the horse power developed by this turbine if the head were increased to 325 ft?

17. A Pelton wheel develops 1000 horse power under a head of 750 ft. How many cubic feet of water per minute does it use?

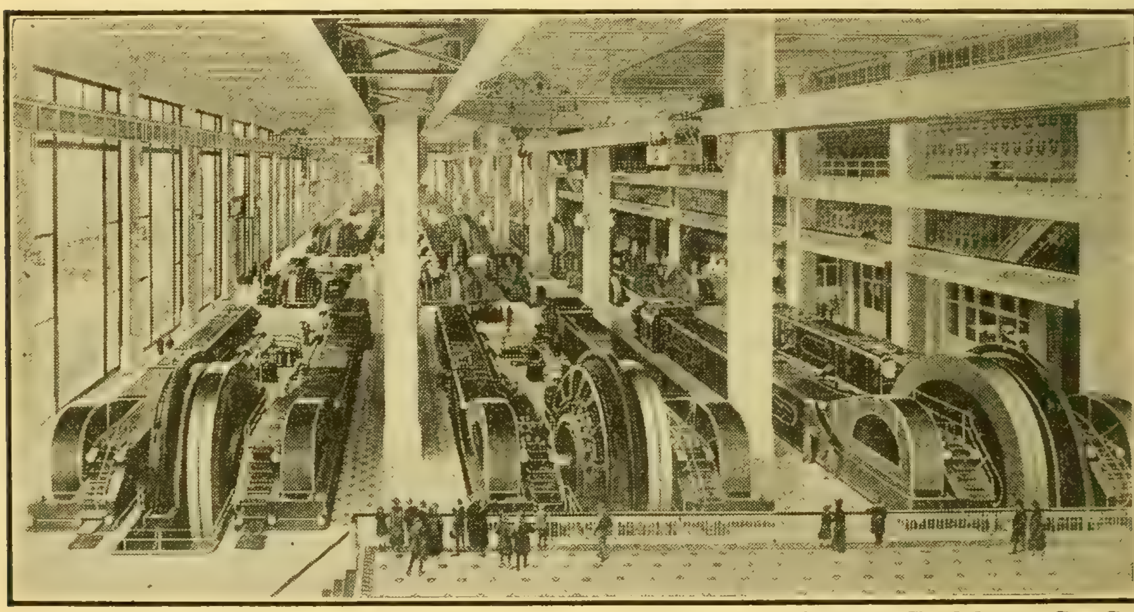
18. Outline all the transformations of energy in a hydro-electric system from the water in the reservoir to the lamps lighted by the generator.

19. Write a paragraph on the importance of conservation of the water-power resources of the country.

CHAPTER XXXIV

STEAM AND GAS ENGINES

440. Machines and Engines. — When primitive man encountered tasks that were too difficult for his unaided strength, he slowly evolved the simple machines mentioned in an earlier chapter. With these machines his own physical strength



Courtesy Ford Motor Car Co.

FIGURE 642. — POWER PLANT OF FORD MOTOR CO.

Exhaust gases from gas engines heat boilers for steam engines, thus increasing the power obtained from the fuel.

enabled him to do many things otherwise impossible. These machines, however, had one great defect from his standpoint: they required an input of as much human energy as they delivered in useful output — without considering the usual friction losses. In other words, just as much work had to be done, but with the force applied smaller than the resistance overcome.

As the earth's human population increased, the difficulty of securing food, shelter, and clothing increased so much that to-day we could not, even if we were willing, supply the human energy necessary to do the work of satisfying the world's needs. Once men enslaved their conquered enemies to do their work, or passed it on to the women, or used domesticated animals to drive their crude machines. Thus, while machines were invented to make work easier, engines were devised to release most of the workers for other tasks. As motive power for these engines, wind, water, steam, and gas have been used.

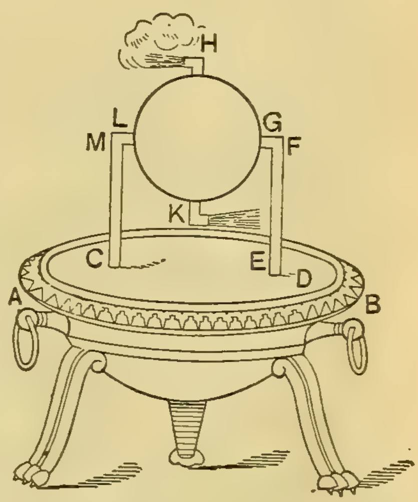


FIGURE 643. — HERO'S ENGINE.

AB, boiler; *MF*, hollow axles; *HK*, nozzles.

441. Early Steam Engines. — The earliest steam engine is attributed to Hero. A sphere, mounted so as to revolve, received steam from a boiler through hollow axles (Figure 643). When steam was permitted to escape through bent nozzles, the sphere itself revolved, much as a rotary lawn sprinkler or a Fourth of July pinwheel does, because of the reaction of the atmosphere against the escaping steam. Nothing of this idea but the fact that steam under pressure could do work came down through the Middle Ages.

In Newcomen's engine (Figure 644) steam from a separate boiler was admitted below the piston and the piston was raised. At the proper time, the steam supply was shut off and water was sprayed into the cylinder. The water condensed the steam; the interior of the cylinder became almost a vacuum; and air pressure above the piston forced the piston down, giving a power stroke. The water spray,

however, cooled the cylinder so much that about 90% of the next charge of steam condensed on the cold cylinder walls, leaving only about 10% of the steam to do the useful work of pushing up the piston.

To avoid this great waste of heat, Watt, in 1763, added a separate condensing chamber below the cylinder. The cylinder walls were not cooled by the cold water spray but as the air still followed the piston into the cylinder, the walls were cooled to some extent by the cold air.

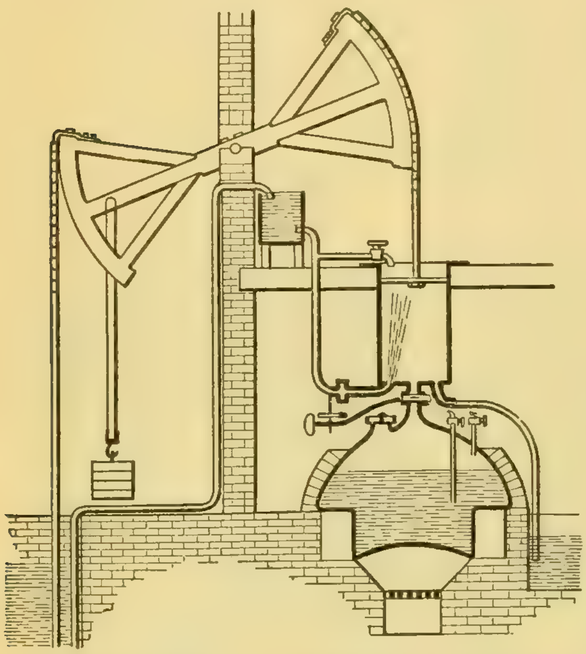


FIGURE 644. — NEWCOMEN'S ENGINE.

The boiler, cylinder, and piston at the right were used to pump water from the well at the left.

442. The Double-acting Engine. — At this stage of development only a little ingenuity was required to arrange the inlet and exhaust passages, or *ports*, in such a way that steam could be admitted to one end of the cylinder, thus pushing the piston in one direction, while at the same time an exhaust port let out the expanded steam from the other end of the cylinder. Reversing the valves at the proper instant reversed the direction of the piston. By this means, and also by surrounding them with a steam jacket, the cylinder walls were kept hot at all times and most of the heat energy of the steam was utilized in doing useful work rather than in reheating the cylinder walls.

Watt found a very crude and inefficient engine, but his improvements left a slide-valve engine whose basic principles have been but slightly changed since his time.

443. How the Steam Runs the Engine. — When steam is admitted to one end of the cylinder, it exerts a pressure on the piston nearly as great as the pressure in the boiler. When the valve cuts off the steam, the elastic force of the steam already in the cylinder continues to act against the piston. This pressure, however, diminishes as the piston moves for-

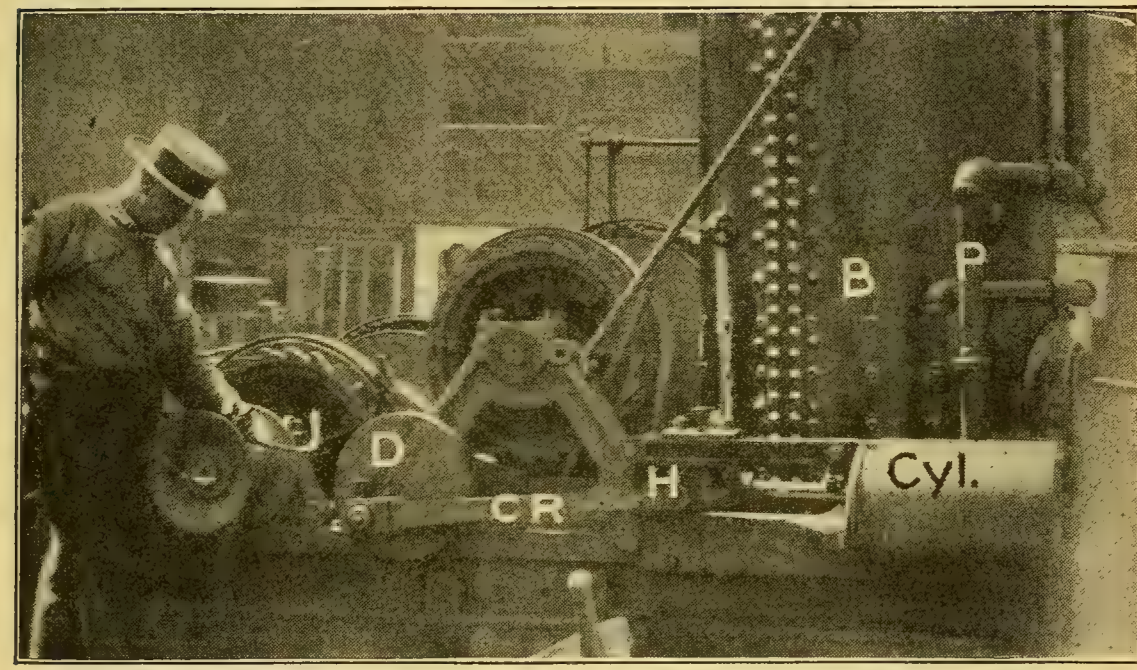


FIGURE 645. — A STEAM HOISTING ENGINE.

Steam flows from the boiler (*B*) through (*P*) to the steam cylinder. The connecting rod (*CR*) joins the crosshead (*H*) with the crank disk (*D*).

ward and the space occupied by the steam increases (Boyle's Law).

A piston rod transmits the back-and-forth motion of the piston to a crosshead (Figure 645). Pivoted to the crosshead at one end and to the crank at the other, is a connecting rod, which changes the back-and-forth motion of the crosshead into the rotary motion of the crank, shaft, flywheel, and driven machinery. Compare this change in motion with that between the treadle and belt wheel of a sewing machine.

Fastened on the crank shaft is an *eccentric* (off center)

disk. Since the eccentric turns with the shaft, it acts like a crank, and by means of the eccentric rod and valve rod, gives the valve the motion described below.

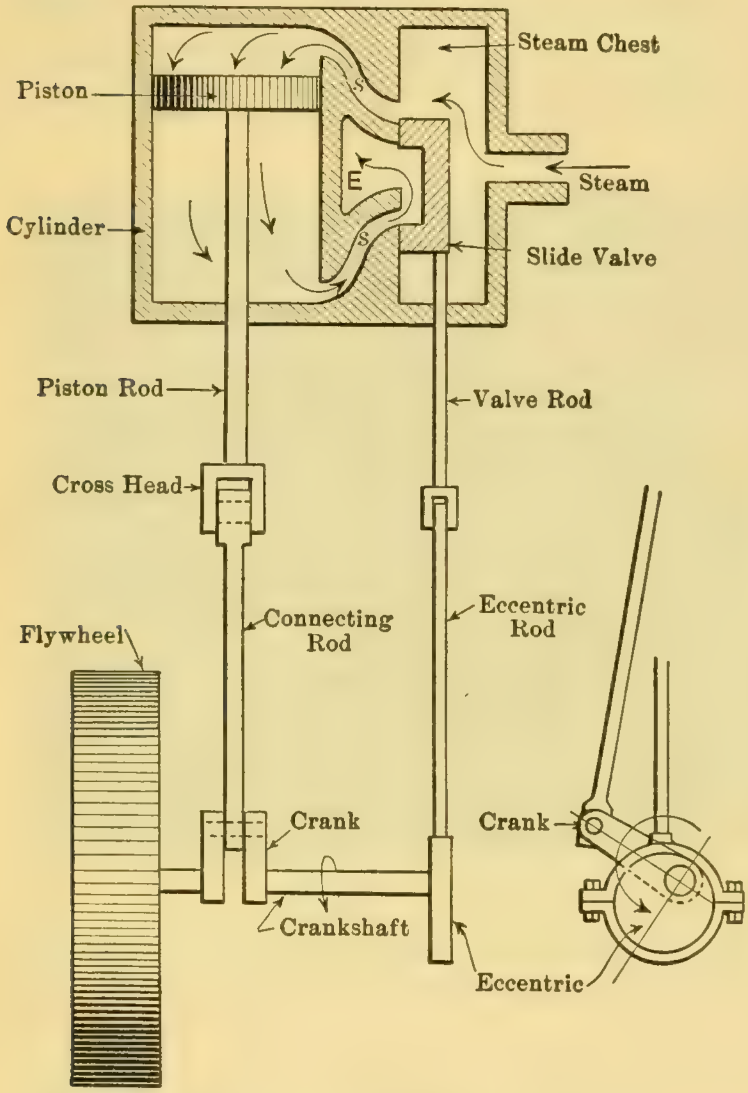


FIGURE 646. — SLIDE VALVE ENGINE.

The cylinder and steam chest are sectioned to show steam passages and slide valve. At the right is shown an end view of shaft, eccentric, and crank.

444. Valve Control.—There are two common methods of valve control in the reciprocating steam engine, slide valves and rotary valves. In the slide-valve type (Figure 646) a steam chest receives the live steam from the boiler. Leading from the steam chest to the cylinder are two openings, or ports (S, S), while a third opening (E) leads from the steam chest either to the outside air (non-condensing, Figure 647) or to a condenser (condensing type, Figure 648). A slide valve, which is like a shallow thick-walled cup of metal, is moved back and forth over the three openings by a rod connected to an eccentric on the main shaft. The general motion of this slide valve is opposite to that of the piston, so that when the piston has reached one end of the cylinder,

the valve has moved far enough the other way to allow steam to enter that end of the cylinder and push the piston back. At the same time the valve permits the dead steam from the other side of the piston to pass out *under* the valve into the exhaust port, as shown by the arrows.

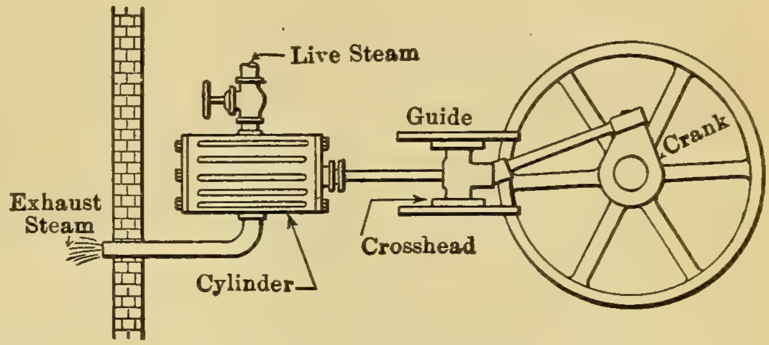


FIGURE 647. — A NON-CONDENSING ENGINE EXHAUSTS INTO THE AIR.

In large engines, the valve is set to shut off the entry of steam when the cylinder is about one fourth full of live steam. In smaller engines the steam is not allowed to expand so much in the cylinder, thus giving more power but less efficiency.

A Corliss-type engine (Figure 649) has an inlet valve and an exhaust valve at each end of the cylinder, making four valves in all. These valves are automatically rotated by a complicated mechanism driven by eccentrics on the engine shaft. Heat losses are reduced because the inlet and exhaust passages are short and each has a nearly constant temperature.

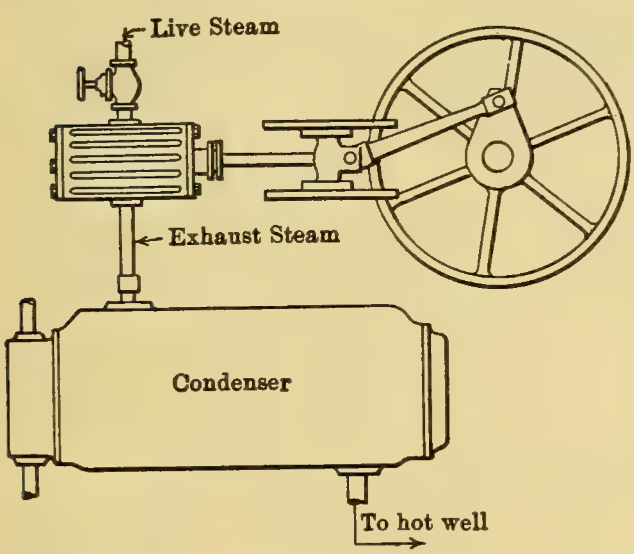


FIGURE 648. — The back pressure of the atmosphere against the piston is lessened by condensing the exhaust steam.

445. Multiple-expansion Engines. — As the steam in the cylinder expands, its temperature falls. When steam is admitted to the other side of the piston on the return stroke, some of its

heat energy is used in warming up the cold cylinder walls and condensation is likely to take place. Multiple-expansion engines are designed to reduce this loss by reducing the range of temperature in each cylinder. In *compound* or double-expansion engines, the partially expanded steam from a small cylinder is passed into a larger cylinder, where it expands still farther (Figure 650). Triple- and quadruple-expansion engines still farther reduce the temperature range per cylinder, and are used where large amounts of power are to be developed or where compactness is essential, as on shipboard. Such engines exhaust into a condenser (Figure 651), to obtain the additional energy available in the steam below atmospheric pressure.

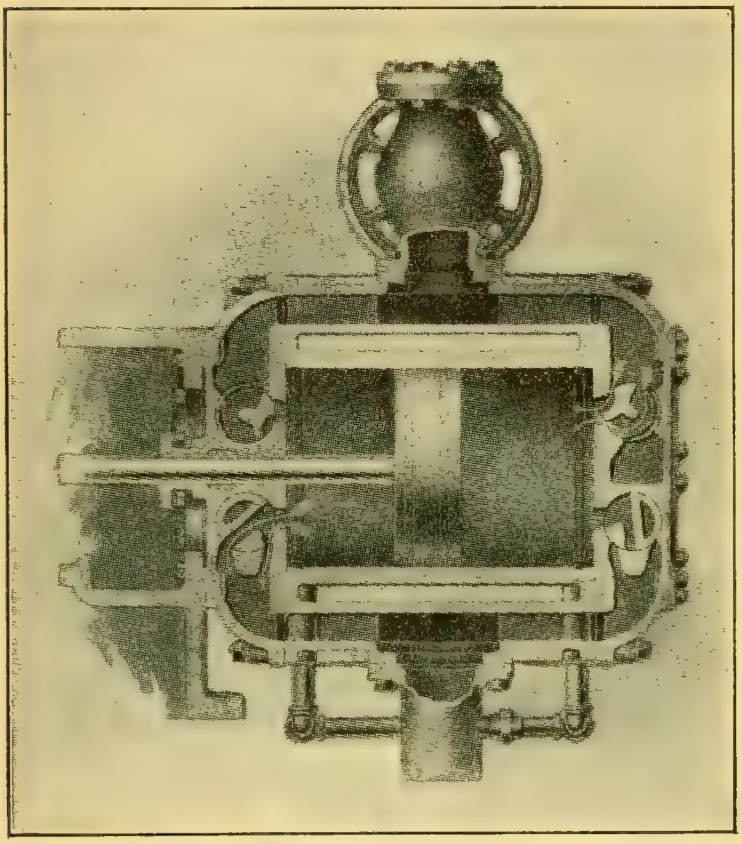
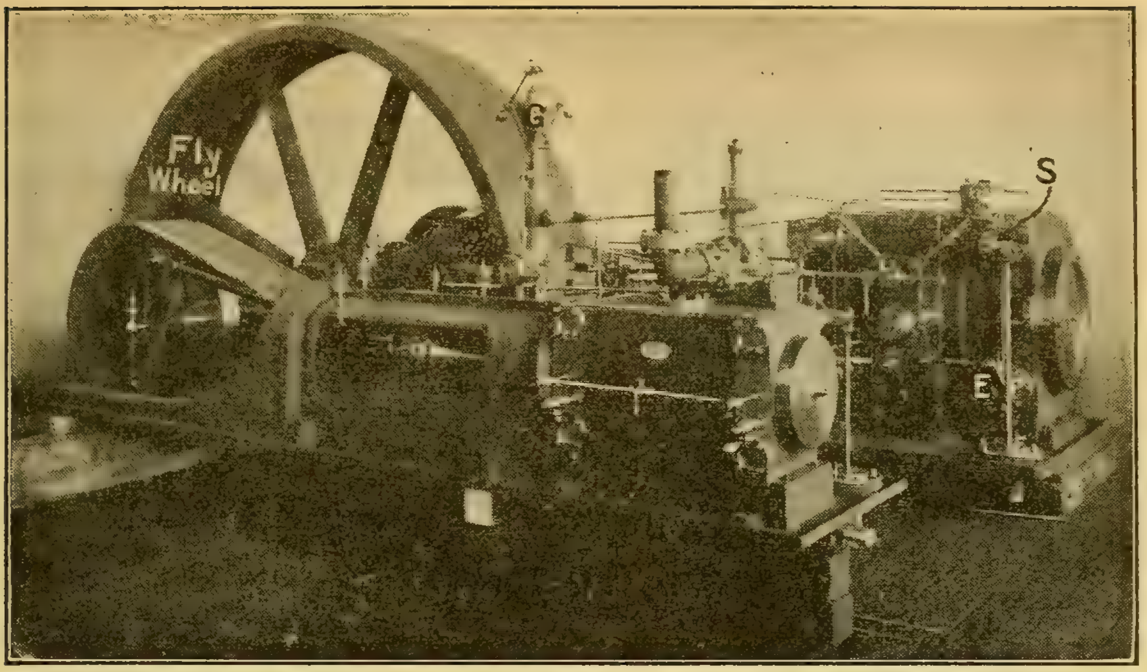


FIGURE 649. — CORLISS ENGINE SECTION.

The steam valve at the top right is admitting steam, and the exhaust steam is passing out the lower left valve. The other two valves are closed.

446. Steam Turbines. — The reciprocating (back-and-forth) motion of the piston type of engine has several disadvantages. The turbine engine secures smoother operation with higher efficiency. The windmill and the water turbine are applications of the same principle, *i.e.* when a fluid stream is directed against curved blades set at right angles to



© *Ewing Galloway.*

FIGURE 650. — COMPOUND CORLISS ENGINE.

S is a steam valve and *E* an exhaust valve on the low-pressure cylinder. The high-pressure cylinder is in the foreground. Note the complicated system of rods necessary to operate the valves.

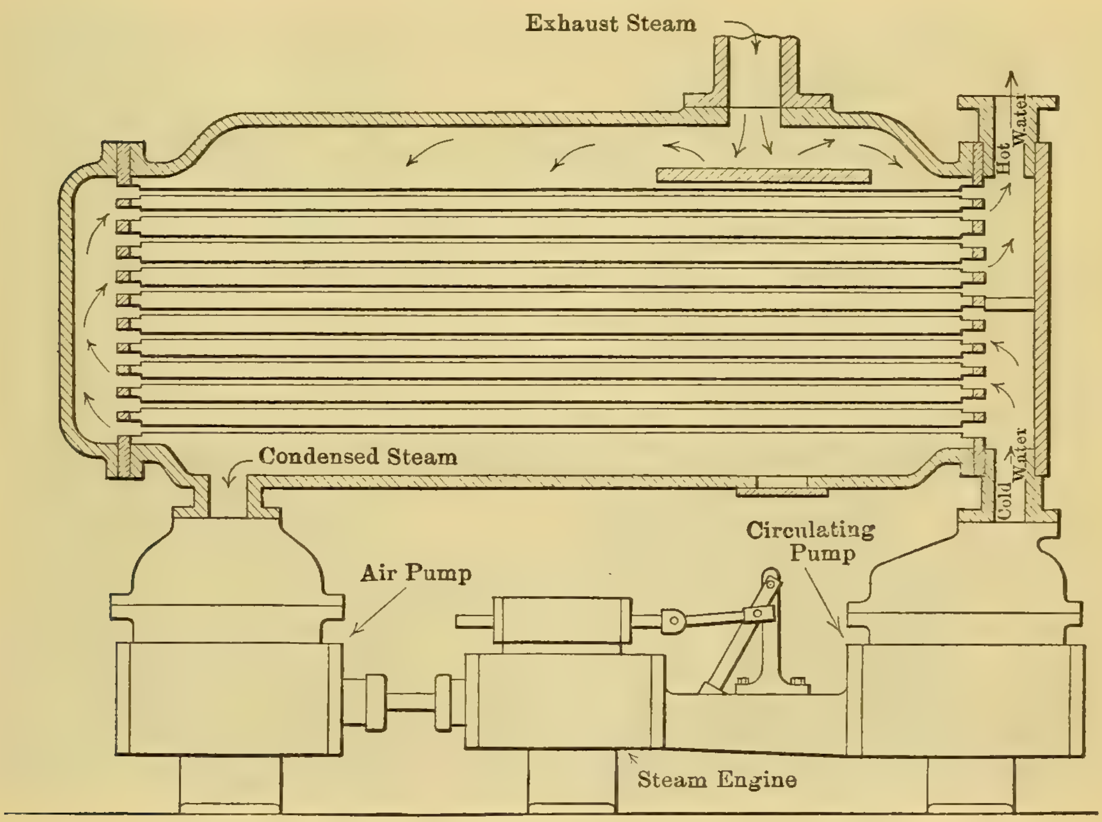
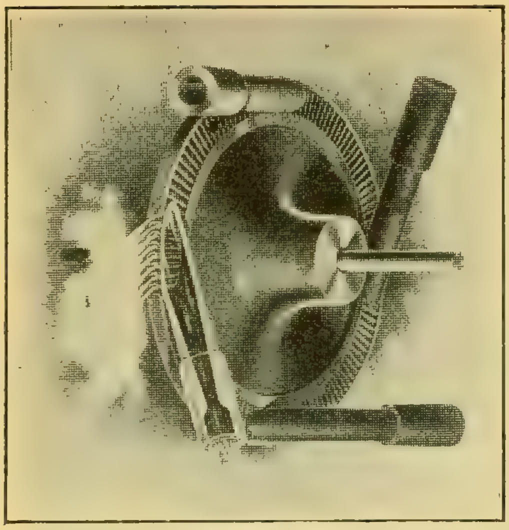


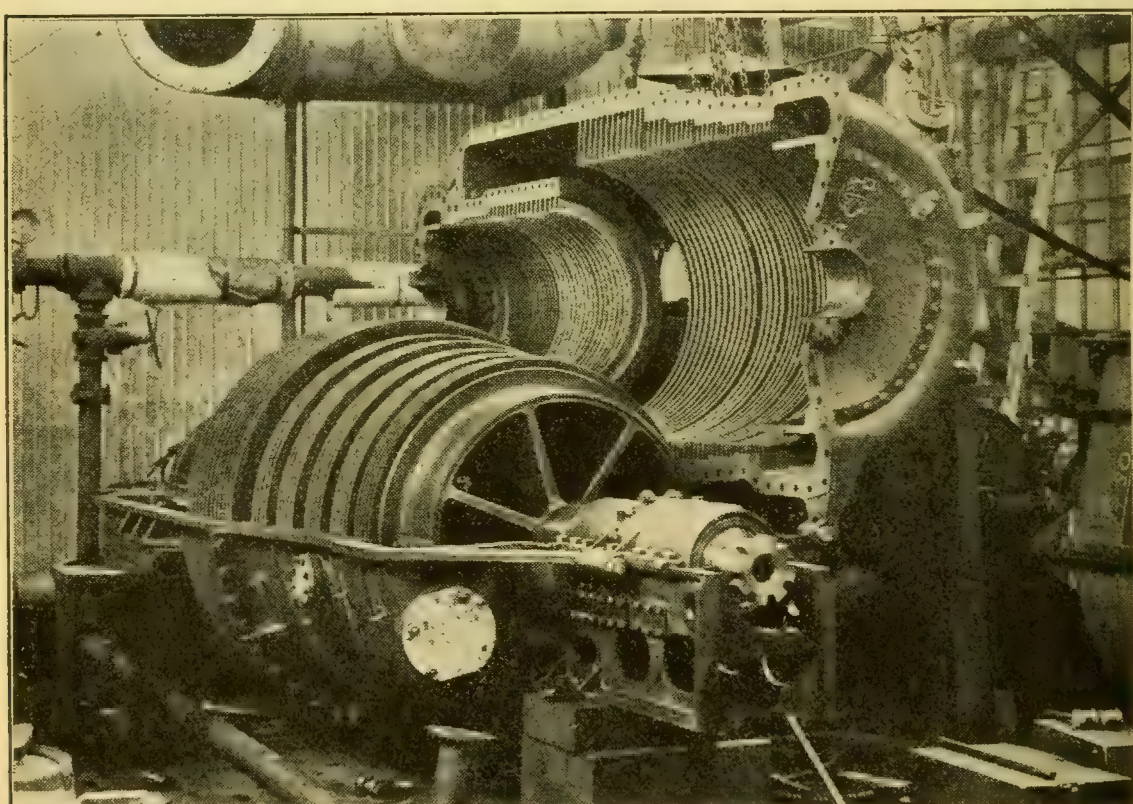
FIGURE 651. — SURFACE CONDENSER (SECTION).

The circulating pump drives cold water through pipes ; the exhaust steam is condensed on the outside of these pipes, and removed by the air pump. The small engine operates both pumps.



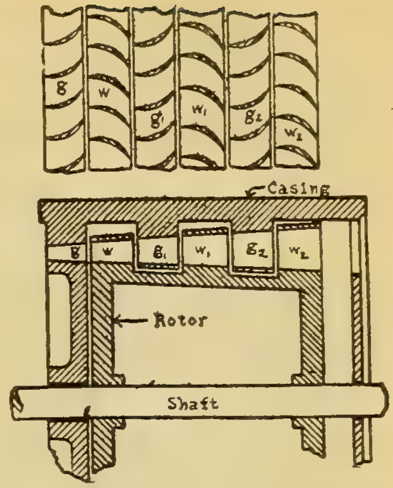
Courtesy of De Laval Steam Turbine Co.
FIGURE 652. — VELOCITY TURBINE.
Steam reaches a tremendous velocity in the expanding nozzles.

a shaft, the shaft will be made to rotate. In a steam turbine, curved blades like those of an electric fan are set on a shaft and the entire rotating part of the engine is inclosed in a case. Steam, directed against the blades, turns the shaft on which the blades are set either by the velocity of the steam current (De Laval, Figure 652), or by the expansion of the steam between the blades (Parsons, Figure 653), or by a combination of both. In the Parsons



Courtesy Bath Iron Works.
FIGURE 653. — PARSONS TURBINE.
Rows of stationary blades on the raised half of the casing fit between similar rows on the turbine rotor. The blades increase in size from right to left to provide for the expansion of the steam.

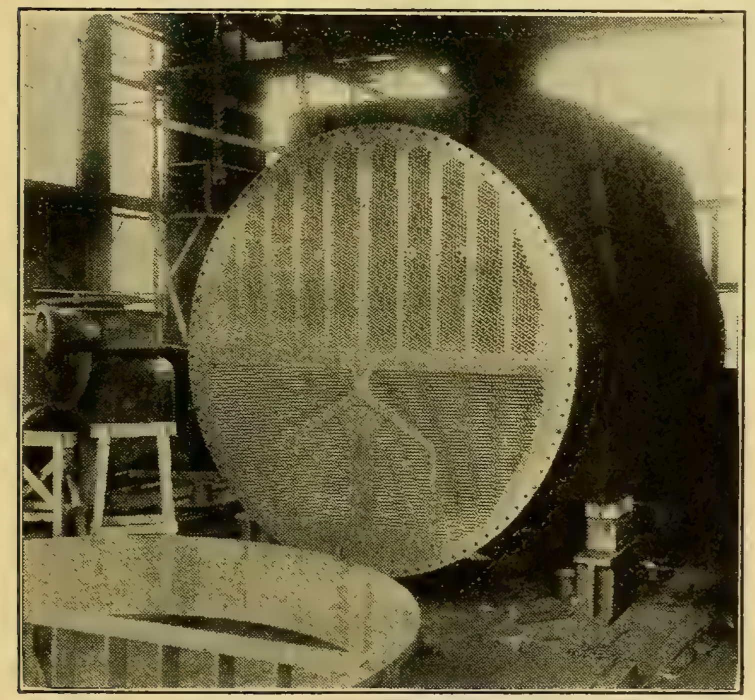
type, to permit the steam to expand as much as possible, a series of rotating blades, separated by alternate sets of stationary blades with reversed curvature (Figure 654), are arranged along the shaft. When steam at high pressure is brought into the turbine case, the steam pushes against the first set of rotor blades, slips through the adjacent set of casing blades, and is redirected against the second set of rotor blades, moving them in the same direction as the first set. Each set of blades takes up a portion of the energy of the steam and lets the steam expand a little more, until it leaves the turbine case at very low pressure.



Reproduced from Meyers' "Steam Turbines" by permission of the U. S. Naval Institute.

FIGURE 654. — TURBINE BLADES.

g, stationary; *w*, rotating. Shape of blades shown above.



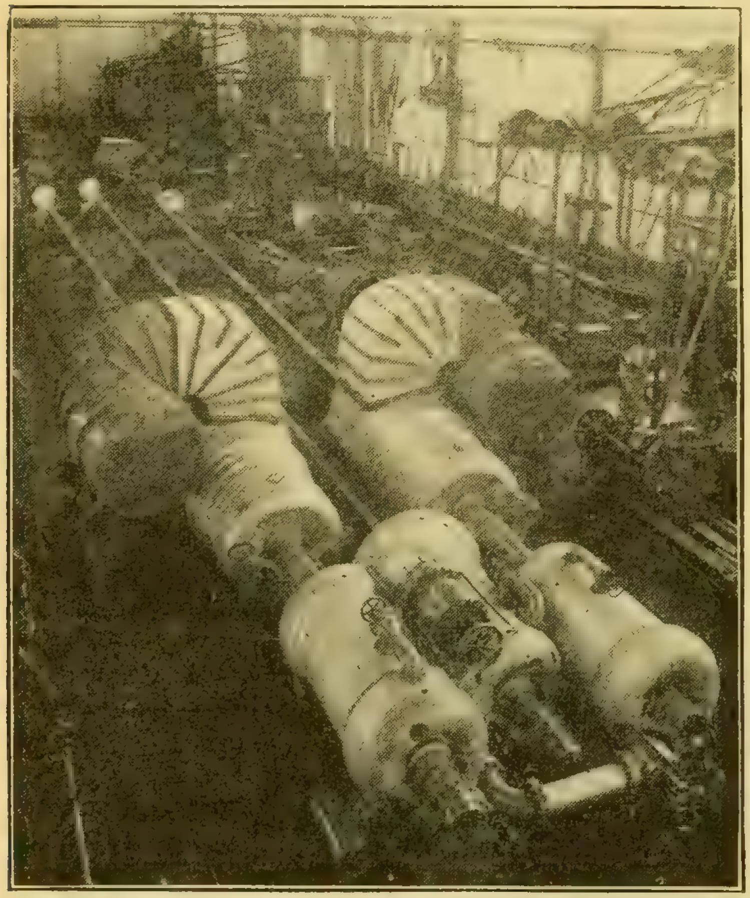
Courtesy Wheeler Condenser and Engine Co.

FIGURE 655. — LARGE SURFACE CONDENSER.

The end connecting with the circulating pump lies on the floor in front. Note the very large number of condenser tubes.

Since heat and mechanical losses are less in the turbine, it may have higher efficiency than the ordinary reciprocating engine, if there is a high vacuum in the condenser (Figure 655). The turbine runs smoothly, without vibration, has few parts to get out of adjustment, occupies only a fraction

of the space of a reciprocating engine of the same power, and in ships (Figure 656) by its gyroscopic effect gives a high degree of steadiness. It runs at speeds too high for many purposes, necessitating the use of reducing gears, and it is not usually designed to be reversed. Due to their economy of operation and of space, steam turbines are the type of engines most frequently installed in large power stations.



Courtesy Bath Iron Works.

FIGURE 656. — TURBINE EQUIPMENT FOR DESTROYER.

The two outside turbines drive the ship forward and the inner one is used for backing. The screws are seen in the background.

447. Steam Boilers.—A steam boiler, in its simplest form, is a strong metal cylinder, so built that the hot gases from the fire pass over as much surface of the boiler as possible before escaping to the chimney. This *heating surface* is increased in many ways. The locomotive boiler (Figure 657) is a good example of the *fire-tube* boiler. The hot gases from the fire box pass through tubes extending horizontally through the water space. Thus the heating surface includes the area of the fire box walls and the area of the fire tubes.

The Babcock and Wilcox boiler (Figure 658) is a typical *water-tube* boiler. An inclined drum at the top is connected

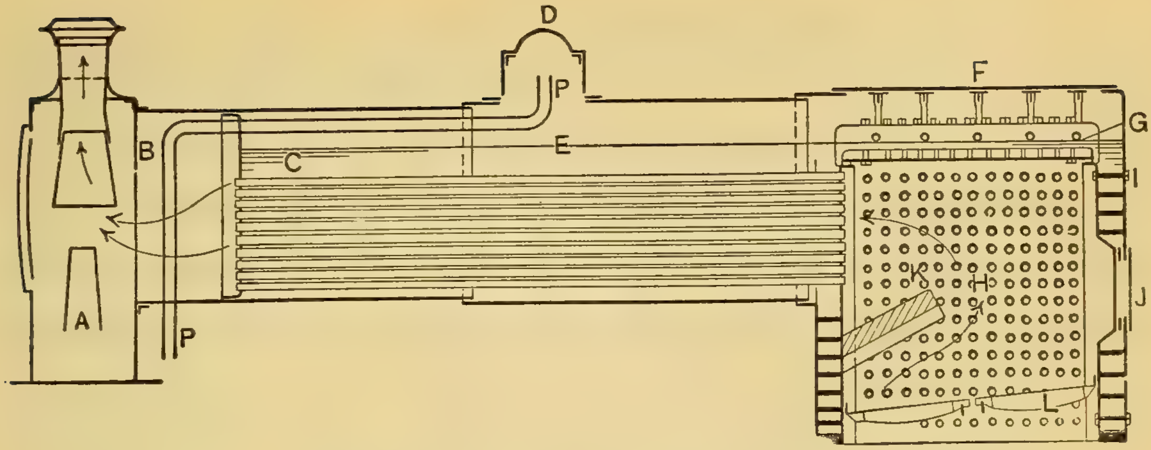
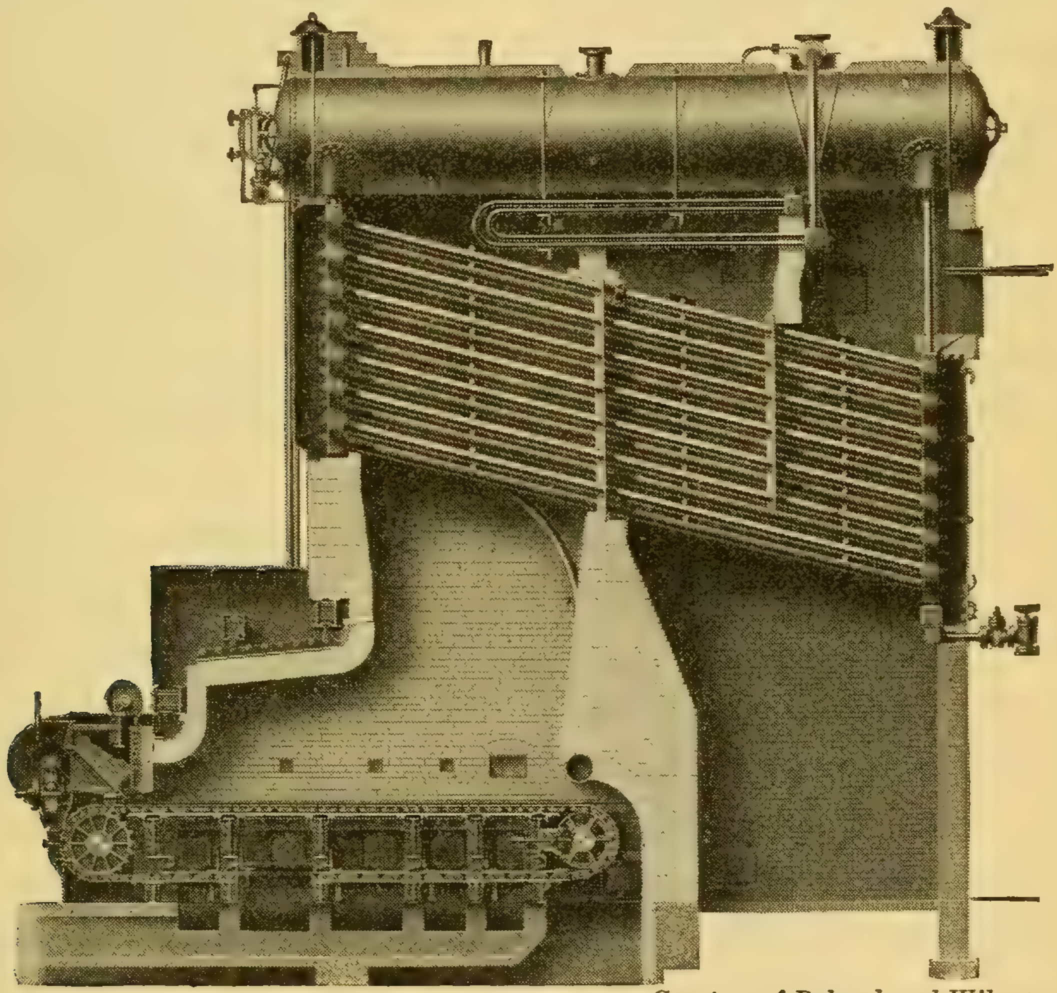


FIGURE 657. — LOCOMOTIVE BOILER.

Fire box at right. The space surrounding the fire tubes is filled with water (*C*). Dry steam collects in the dome (*D*) and is carried to the engine through the pipe *P*.



Courtesy of Babcock and Wilcox.

FIGURE 658. — BABCOCK AND WILCOX BOILER.

Hot gases pass up, down, and up from the fire to the chimney at the top, right. Water circulates from the drum down the rear header pipes, then through the inclined pipes to the front header.

by the vertical headers at each end to a large number of tubes. The tubes, headers, and part of the drum are always full of water. All these metal parts are inclosed in a fire-brick setting, so built that the hot gases must take a devious path to reach the chimney. In this way, a larger heating surface is secured. The inclination of the tubes and drums, and the location of the fire box, cause convection currents forward through the tubes and backward through the drum. The boiler is therefore a "quick steamer."

448. Work Done by a Steam Engine. — Work is always calculated by multiplying force by distance. In the reciprocating engine, the *force* is the average pressure of the steam × the square inches of piston area; the *distance* is the length of the stroke in feet. If horse power is to be determined, the foot pounds per stroke are multiplied by the number of strokes per minute, and the product divided by 33,000.

$$\textbf{Horse Power} = \frac{\textbf{Av. Press.} \times \textbf{In}^2 \times \textbf{Length of Stroke} \times \textbf{Strokes per minute}}{\textbf{33,000}}$$

449. Efficiency of a Steam Engine. — When water is boiled under pressure in an inclosed container, the steam formed has the same pressure as that upon the water. Thus it is possible in a closed boiler to obtain a pressure of several hundred pounds per square inch at a boiling point much above 100° C. Heat is required to raise the water to the boiling point, a great deal more heat is required to convert the water into steam (§ 136), and then the steam is in some cases superheated. In the engine, the steam gives off its heat energy by expanding against the piston or the turbine blades. But the steam in expanding cannot give off the heat required to raise the water to the boiling point, nor can

the heat of vaporization be converted into work. In the best type of stationary engine less than one fifth of the heat of the coal can be delivered by the engine as useful work. In the steam locomotive, which cannot economically transport the cumbersome condensing equipment, about one sixteenth to one twentieth of the available heat energy is converted into work. To get all the useful work from steam, it would have to expand until its temperature was lowered to absolute zero, without heat losses of any kind.

450. Internal-Combustion Engines. — When natural gas and gasoline became available for fuel, attempts were made to use them in engines that would burn the fuel in the cylinder rather than under a distant boiler. In this way much of the heat waste of the steam engine might be avoided. The gasoline engine of to-day is based upon the principle of burning the gasoline, in vapor form, in the cylinder of the engine, and then utilizing the expansion of the heated gases to push a piston in the cylinder. Four things must be done to secure the continuous repetition of this process. 1. The gas and the air required for its com-

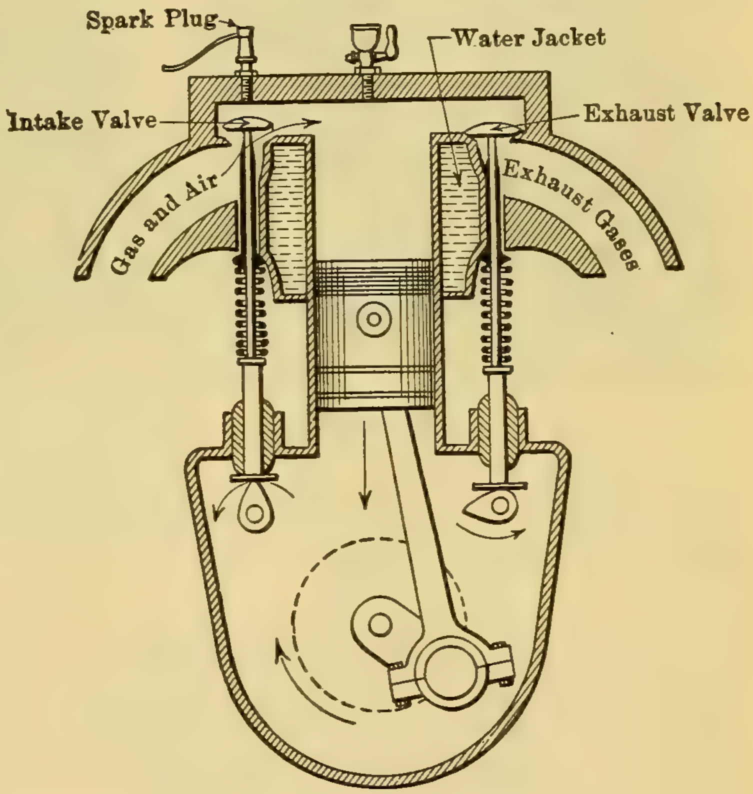


FIGURE 659. — GASOLINE ENGINE.
The position shown is near the end of the admission stroke.

bustion must be admitted. 2. The mixture must be compressed. 3. The mixture must be ignited. 4. The burnt gases must be exhausted. In order to bring about the four steps in this cycle of operation, two valves and a spark plug are set in or near the top of the cylinder (Figure 659). The valves are operated usually by cams on a half-time gear driven by the main shaft, although there are several kinds

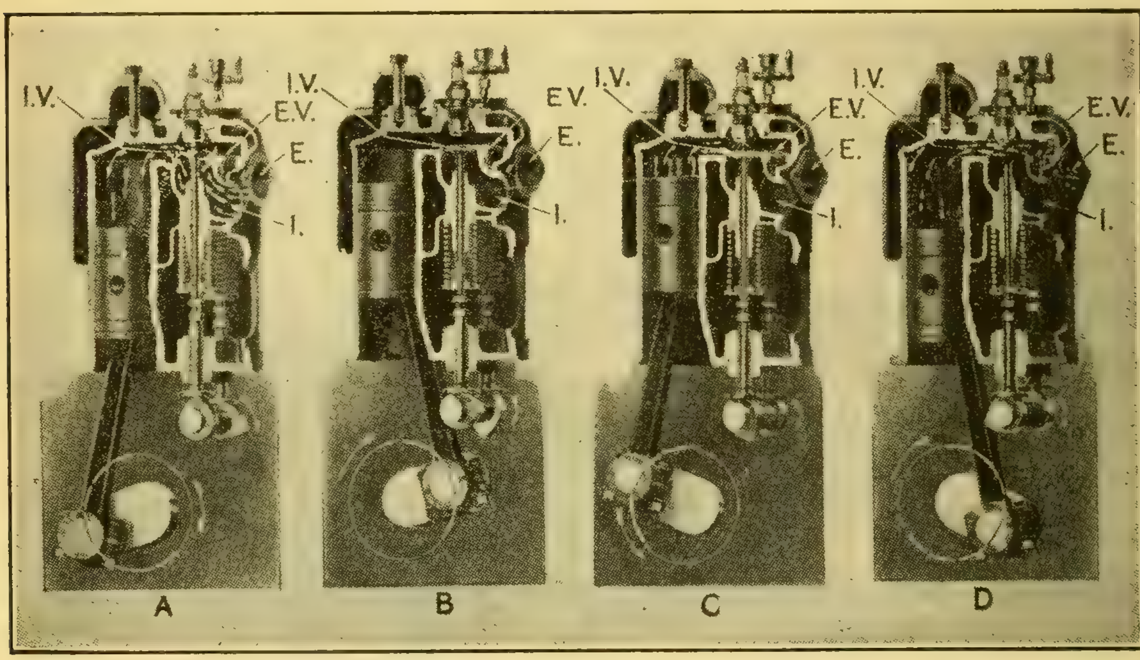


FIGURE 660. — FOUR-STROKE CYCLE.

A, Admission. *B*, Compression. *C*, Power. *D*, Exhaust. Note in each case which valve is open. *I.V.*, intake valve; *E.V.*, exhaust valve; *I*, intake passage; *E*, exhaust passage.

of valves and valve mechanisms. The spark is furnished by an induction coil or a magneto when a rotating switch, called a *timer*, makes connections at the proper intervals (Figure 679).

451. Four-Stroke Cycle. — Let us suppose that the cylinder has just been emptied of waste gases and the engine is ready to begin a new cycle. As the piston moves away from the closed end of the cylinder, the inlet or admission valve is opened by a cam (Figure 660, *A*). Through this

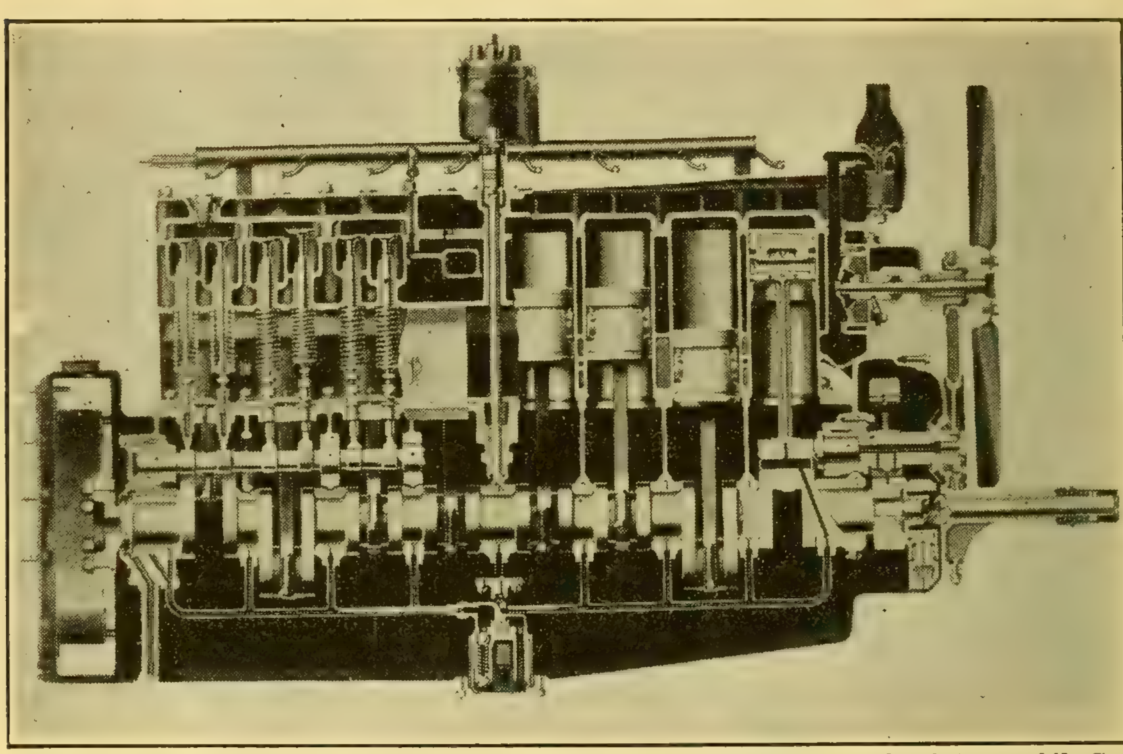
valve flows a mixture of gasoline vapor and air, filling the cylinder. When the piston moves back toward the closed end of the cylinder, the gases are compressed to a fraction of their original volume (Figure 660, *B*). Just as, or just before, the compression is greatest, depending on how the spark is set, the timer makes contact and a spark jumps the gap in the spark plug and the mixture of gases is exploded (Figure 660, *C*). When the engine is being started, or is running slowly, the mixture is ignited just as the piston is beginning the power stroke, as earlier ignition might tend to force the piston backward. But when running at higher speeds, the "spark is advanced." This means that the ignition begins shortly before the piston has completed the compression stroke. The burning of the mixture takes a measurable time, but at high speed it is necessary to begin the burning before the piston begins the power stroke, in order to give time for the combustion to complete itself before the power stroke begins.

The explosion of a gas is nothing more than a rapid burning of the gas. The explosion is accompanied by a great increase in pressure, mostly due to the heat caused by the burning. This expansion drives the piston toward the open end of the cylinder with the one power stroke out of the four strokes in the cycle. During the fourth stroke (Figure 660, *D*), as the piston moves toward the closed end again, the exhaust valve is opened and the waste gas is pushed out by the piston. The engine is then ready to repeat its cycle.

When the engine is being started, it is obvious that the movement of the piston to secure admission, compression, and explosion must be brought about by outside force. This force is supplied either by a hand crank or a self-starter. Once the engine is running, much of the energy of the power

stroke is taken up by a heavy flywheel. The inertia of this flywheel carries the engine on through the exhaust, admission, and compression strokes until the next explosion occurs.

452. Multiple Cylinder Engines. — When the engine is heavily loaded, the energy taken up by the flywheel may not carry the engine to the next power stroke, and the engine



Courtesy of Packard Automobile Co.

FIGURE 661. — EIGHT-CYLINDER AUTOMOBILE ENGINE.

Four cylinders shown in section at right; the valves for three of the other cylinders are shown at the left.

máy stall. To avoid this difficulty most gas engines are grouped in sets of four, six, eight, or twelve engines operating a single machine (Figure 661). Such groups are known as four-cylinder motors, etc. These motors give small frequent impulses to the machinery to be driven, rather than one large, infrequent power stroke. Do not confuse the term *four-cycle,* which means four separate steps in operation, with the term *four-cylinder,* which means four engines grouped together.

453. Diesel Engines. — This type of engine is rapidly coming into favor as a marine engine, because of the small space required for itself and its fuel, and because of its low operating cost. The principle of its operation is that when oil is sprayed into the hot cylinder of the engine, it is vaporized. The air necessary for combustion is admitted to the cylinder and then highly compressed before the oil is sprayed in at the end of this stroke. The high temperature that results from the compression ignites the fuel oil as fast as it is sprayed in.

Since the engine works at a very high temperature, it can use low-grade oils, which would not vaporize at the operating temperature of the ordinary gas engine. Because of the high pressure, the cylinder walls must be so heavy that the engine is not adapted for automobile or airplane use.

As noted, the engine is useful for warships, such as submarines and destroyers, and many merchant ships are replacing steam engines with Diesel engines in order to secure more cargo space and greater economy in labor costs. These engines are also used to some extent on land.

454. Uses of Internal-Combustion Engines. — It would be difficult to make a list of the various uses to which these engines are put. In twenty-five years they have brought about a complete revolution in the life and habits of a large portion of the country. Besides their obvious application to the automobile, we must remember that the airplane owes its success to the light but powerful gasoline engine. In many less spectacular ways, man has been aided by a cheap, easily operated source of power, which drives farm and manufacturing machinery; operates mills, mines, and quarries; and in general relieves the world of much of the drudgery

of labor and the tedium of idleness. The disquieting feature of their use is the possible exhaustion of the available fuel supply. An extension of the variations of gasoline engine construction and its accessories will be found in the next chapter.

SUMMARY

Engines are used to do the work that would otherwise be done by man.

Engines are operated by wind, water, steam, or the explosive force of some combustible gas.

Steam engines are either of the **reciprocating** or **turbine** type. **The piston of a reciprocating engine** is pushed first one way and then the other by the force of the expanding steam, exerted alternately against the opposite sides of the piston.

The amount of work done depends upon how much heat the steam loses while expanding against the piston. Reciprocating engines may be of the slide valve or of the Corliss type.

The slide valve admits live steam alternately to the two ends of the cylinder and dead steam from the cylinder to the exhaust.

The Corliss engine has an inlet and an outlet valve in each end of the cylinder. These valves are operated by a complicated mechanism to let live steam in at one side of the piston and dead steam out from the other side at the proper time.

The turbine engine has one or several bladed wheels in a case. These wheels are driven by the impulse of high-velocity steam, or by the push of high-pressure steam, or by both combined.

Internal combustion engines are operated by the force of expansion of a gas, which is burned within the cylinder. This force is exerted against a movable piston and transmitted to the machinery to be driven.

A four-stroke cycle engine admits an explosive mixture into the cylinder on the first outward stroke of its piston, compresses the mixture on the inward stroke, fires the mixture as the second out

ward stroke begins, making it a power stroke, and clears the cylinder of waste gases on the second inward stroke.

Internal combustion engines are light, compact, powerful, and increasingly simple to operate. They are used in automobiles, airplanes, boats, ships, and for a wide variety of other power purposes.

EXERCISES

1. Compare *machine* and *engine* as to meaning.

2. What different methods has man used to avoid supplying his own physical energy to his machines? Why have these earlier methods become obsolete?

3. Trace the steps in the development of the steam engine previous to the time of Watt.

4. What improvements did Watt make upon the steam engine? Why were these changes effective in making a better engine?

5. Explain the operation of the slide valve. What moves it? How does the general motion of the slide valve compare with that of the piston?

6. What becomes of the waste steam in the non-condensing engine? In the condensing type of engine?

7. Which of these two types in Question 6 is more efficient? Why?

8. Describe the location and explain the operation of the valves in a Corliss engine.

9. Explain how the back-and-forth motion of the piston of an engine becomes a rotary motion of the shaft, flywheel, etc.

10. How is the work done per stroke calculated when the average pressure, area of piston, and length of stroke are known? How is the horse power calculated?

11. Contrast the principle of operation of a reciprocating engine with that of a turbine engine. What are the special advantages claimed for the turbine?

12. Give in brief the difference between the types of turbine engines.

13. Name and describe two types of steam boilers.

14. Discuss the efficiency of the steam engine. What is the reason for its low efficiency?

15. How does the internal-combustion engine differ from the steam engine in the principle of its operation?

16. Which type of engine ought to be more efficient? Why?

17. Name the operating parts that you would expect to find in a simple gasoline engine.

18. How are the valves of a gasoline engine operated? How is the spark produced and timed properly?

19. What four things have to be brought about during one cycle of operation of a four-stroke cycle engine?

20. Describe in order the four steps in the cycle of a four-stroke cycle engine, stating how each step is brought about.

21. How is a gasoline engine caused to make the strokes preceding its first power stroke? What carries the engine to its next power stroke?

22. Explain the difference between four-stroke cycle and four-cylinder engines.

23. Discuss the Diesel engine briefly, covering the principle of operation, economy of operation, and uses.

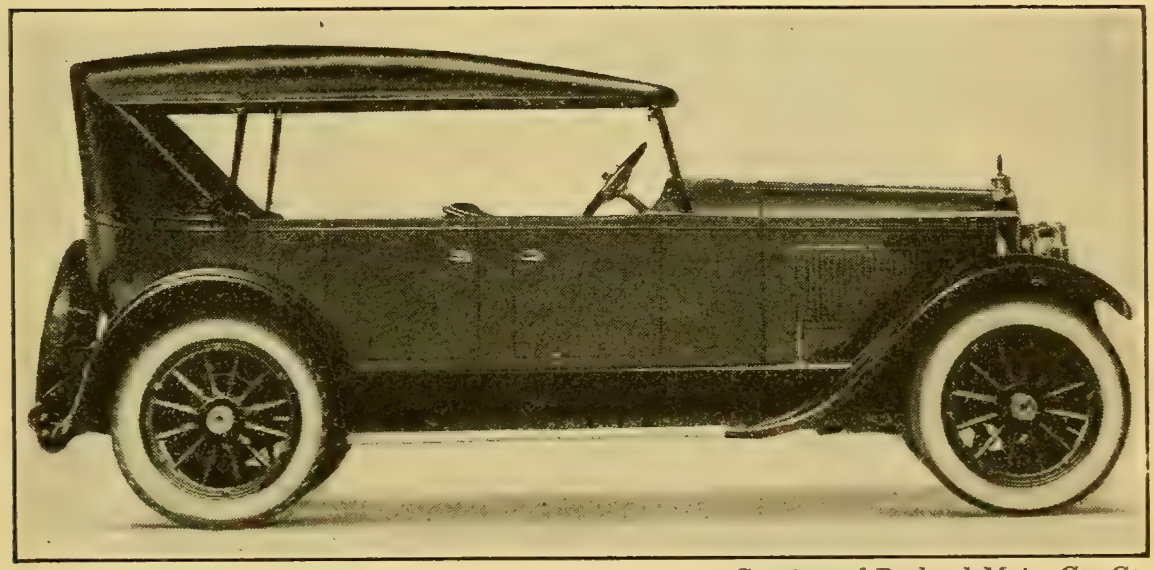
24. What effects have been brought about by the introduction of the gasoline engine?

25. Make labeled drawings of (*a*) a simple slide-valve engine; (*b*) a Corliss engine cylinder; (*c*) a four-stroke cycle gas engine.

CHAPTER XXXV

THE AUTOMOBILE

THERE is probably no single machine in which so many principles of Physics find their application in so small a space as in the modern automobile. Mechanics, heat, light, sound, and electricity, all play their part in the building and operation of man's most useful mechanical means of transportation. A brief study of the automobile may, therefore, serve as an efficient method of reviewing your course in physics.



Courtesy of Packard Motor Car Co.

FIGURE 662. — THE AUTOMOBILE APPLIES MANY PHYSICAL PRINCIPLES.

455. Frame. — We may conveniently consider the automobile as made up of frame, wheels, power plant, body, and accessories. The frames of most automobiles are made of steel, often of special composition, in order to secure the maximum of strength with the minimum of weight. The

two side members are channels (Figure 663), plates of steel, with the edges bent over. By this construction, they make either horizontal or vertical bending difficult. These are connected by the axles, front and rear, and by cross members.

To the frame are attached the wheels, the power plant, and the body. The frame, wheels, and power plant are commonly called the *chassis* (Figure 664). Care is taken in proportioning and placing the weight of the different parts and the load, so that their moments (§ 361) around the front and rear axle will be as nearly the same as possible.

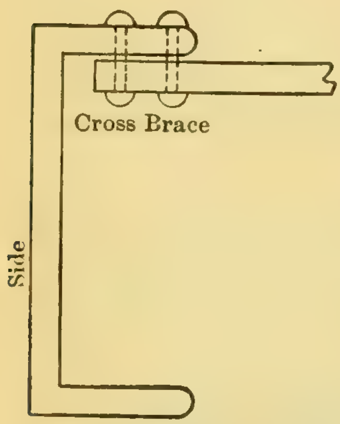
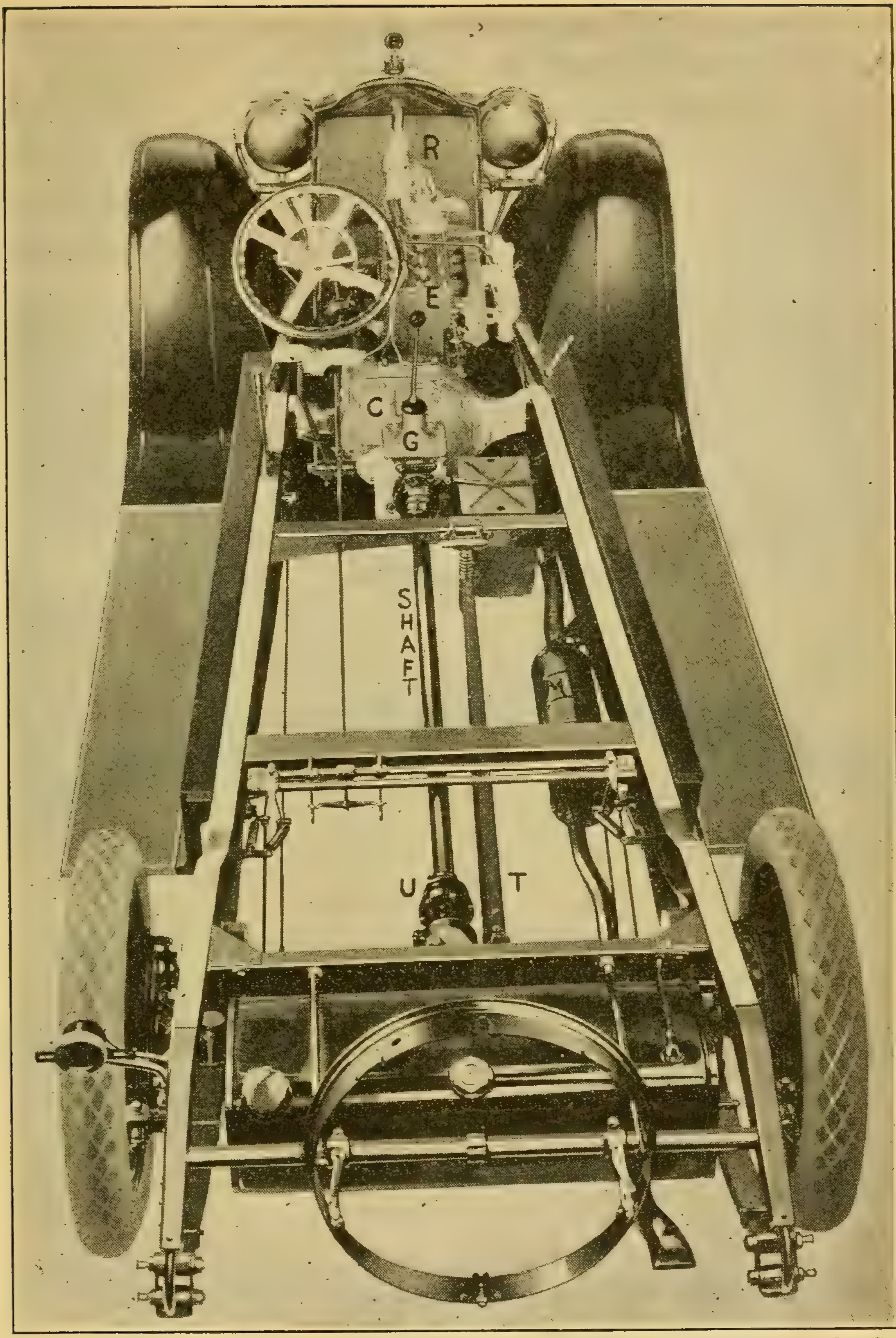


FIGURE 663. — CHANNEL IN SECTION.

456. Springs. — All roads are more or less rough. Those who have ridden in a springless lumber wagon know what it means to have the jars of the road directly transmitted. By interposing springs between the wheels and the rest of the car, the inertia of the parts is taken up by the elasticity of the springs, and of the air and rubber in the tires. Further elasticity is furnished by the frame itself, and sometimes by " air springs " (§ 6).

Both practical considerations of cost and manufacturing methods, and the complexity of the theory of flat springs have led different manufacturers to adopt varying forms of springs. Those most widely used are full-elliptical, half-elliptical, and cantilever springs (Figure 665). Each is adapted to particular weights of parts and a particular distribution of weight. The combination of the inertia of the car and the elasticity of the springs is likely to produce an oscillating system. This is avoided as far as possible in design, and the tendency to oscillate is often further checked by *shock absorbers*. These vary greatly, but have the common



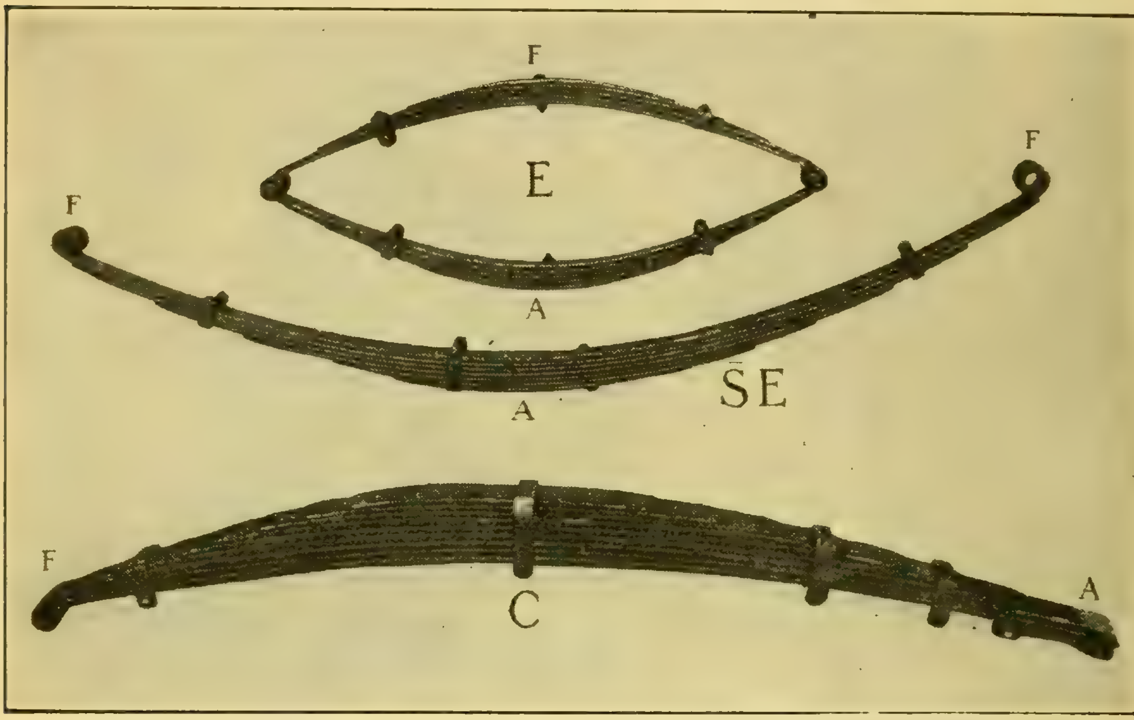
Courtesy of Packard Motor Car Co.

FIGURE 664. — AUTOMOBILE CHASSIS.

R, radiator; *E*, engine; *C*, clutch case; *G*, gear shift; *T*, torque arm; *U*, rear universal.

purpose of permitting the springs to respond freely to a shock, but making their elastic rebound slower.

When a car starts from rest, or stops suddenly, an additional stress on the rear springs is caused by the driving mechanism of the rear axle responding before the inertia of the rest of the car permits it to do so. Long, flexible rear



Courtesy Eaton Spring Co.

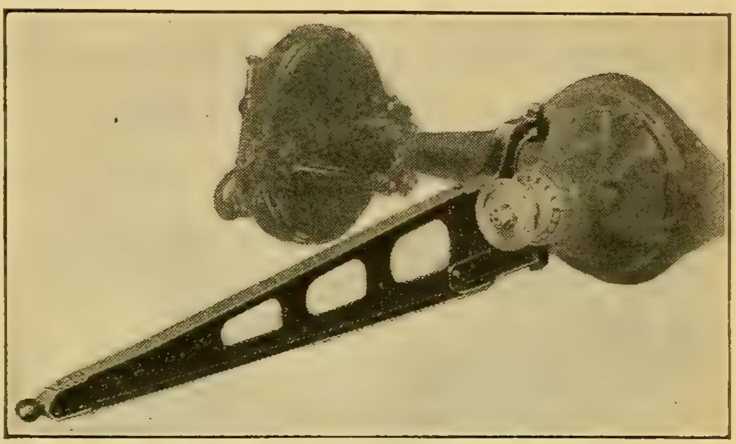
FIGURE 665. — SPRINGS.

C, cantilever; *SE*, half-elliptical; *E*, elliptical. *A* on each spring indicates the point where it is attached to the axle; *F*, the attachment to the frame.

springs will take up this shock, and such cars are said to "drive through the springs." In other cars, a long steel *torque arm* (Figure 666) is attached to the rear axle, and its other end is attached to the frame between two coiled springs.

457. Friction in the Automobile. — The reduction of friction in the moving parts is sought in every possible way. Roller and ball bearings (§ 392) are used whenever possible. An oil pump keeps oil circulating through all engine bearings

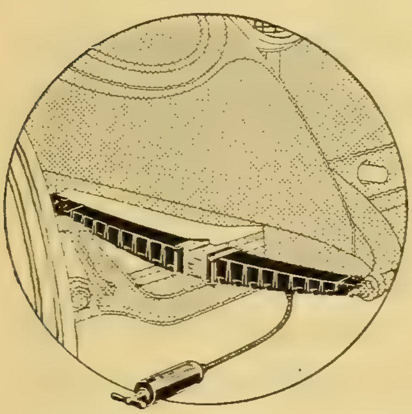
and in some cars, through all bearings. Gears run in grease or heavy oil. Spring bearings (*shackles*) are kept filled with oil or grease, and the spring leaves should be lubricated (Figure 667). There is no factor that contributes more to proper running and long useful life of a car than constant and systematic attention to lubrication.



Courtesy of Packard Motor Car Co.

FIGURE 666. — The torque arm takes shocks in starting and stopping.

At the surface of the tires, it is important to secure as large a coefficient of friction (§ 393) as possible. This is the reason for using corrugated treads on the tires. These take advantage of every inequality of the road. Where there are actual pockets in the surface of the tire, the weight of the car squeezes the air out of the pockets and atmospheric pressure causes greater adhesion.

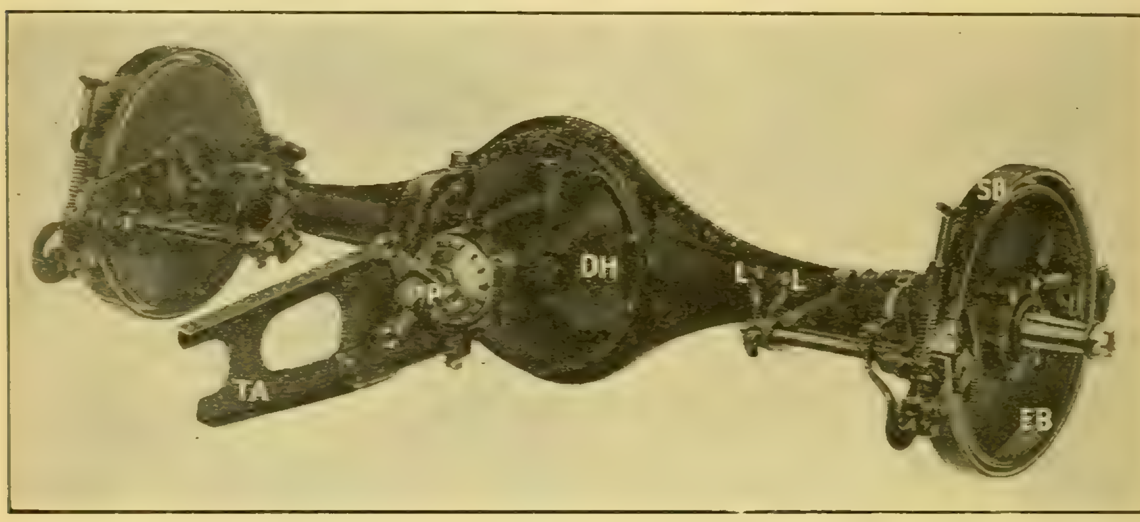


Courtesy Bassick Mfg. Co.

FIGURE 667. — GREASING A SPRING.

458. Brakes. — The great weight and consequent inertia of the automobile make adequate means of checking its motion exceedingly necessary. It would not be feasible to apply brakes to the tires, because of the heating and wear. So *brake drums* of steel are attached to the inside of the rear wheels and sometimes of the front wheels as well, or such a drum is placed on the drive shaft (§ 466). Friction is applied to the drums

by embracing brake bands. These consist of flat circular springs, lined with a woven material, usually consisting largely of asbestos, because of its high coefficient of friction and its resistance to the heat. These brake bands may be made to contract around the outside of the drum, or to expand against the inside. The driver's foot applies force to one set of brakes (*service brakes, SB,* Figure 668) through a



Courtesy of Packard Motor Car Co.

FIGURE 668.—REAR AXLE.

L, L, rear brake levers; *DH,* differential case; *P,* end of driving pinion; *TA,* torque arm.

system of levers and rods; the other set of brakes (*emergency brakes, EB*) is operated by a hand lever at the driver's side.

In order to prevent the car from "skidding" when the brakes are applied, the bands must make contact at the same instant and with equal force on all drums. On this account, equalizing levers and adjustments must be made where wheel brakes are used. The drive-shaft brake is free from this complication, but its drum should be wide to secure adequate friction surface. In going down hills, the brakes may be saved by leaving the engine in gear without feeding gas, thus utilizing the compression of the cylinders to hold the car back.

459. Power Plant.[1] — The power plant of an automobile consists of the engine and certain auxiliaries that produce the power and apply it to the axle of the rear wheels by means of the *transmission system.* The power plant is placed near the front and is supported on the frame of the car.

While there are several types of automobiles electrically driven by a motor supplied with current from storage batteries in the car, nearly all of the automobiles of to-day are propelled by gasoline. The principles and operation of the gasoline engine discussed in §§ 450 and 451 apply equally well to the gasoline engine of a motor car.

The first automobile engine had but one cylinder, but the number has been gradually increased until modern engines have six, eight, and even twelve. The one-cylinder engine had to have a large cylinder and was jerky in its operation. Its power stroke had to give enough energy to the flywheel for this to run the car during the exhaust, intake, and compression strokes. Increasing the number of cylinders increased the frequency of the impulses applied to the flywheel, so that less energy need be stored in the flywheel to carry the car along during intervals between power strokes. Whatever the number of cylinders, all of them must fire while the crankshaft is making two revolutions. Thus a four-cylinder engine applies two power impulses to one revolution of the crankshaft; a six-cylinder, three; and an eight-cylinder, four. The greater the number of impulses applied to the crankshaft per revolution, the smoother will be its operation and the less the vibration of the engine (Figure 669). Increasing the number of cylinders increases the consumption of gasoline per unit of power developed. Hence from this

[1] Students should review gas engines (§§ 450–452) before studying the automobile power plant.

standpoint, the four-cylinder engine is more economical than the multi-cylinder ones. The six-, eight-, and twelve-cylinder motors, however, are more flexible in operation and require less changing of gears.

The valves of multi-cylinder engines are operated by rods pushed up by *cams* or projections on a rotating cam shaft (*CS*, Figure 670). This shaft is turned by means of *timing gears* driven by the engine shaft. The gear on the engine shaft has half as many teeth as the cam shaft gear; consequently the cam shaft makes one revolution to two engine-shaft revolutions. The cams, two for each cylinder, are so set on the cam shaft that the intake and exhaust valves of the various cylinders are opened in the *proper firing order*. This order is so arranged that cylinders firing successively will be located at considerable distance from each other in the engine block, so as to secure an even distribution of forces. The firing order of the Packard Eight is 1, 3, 2, 5, 8, 6, 7, and 4.

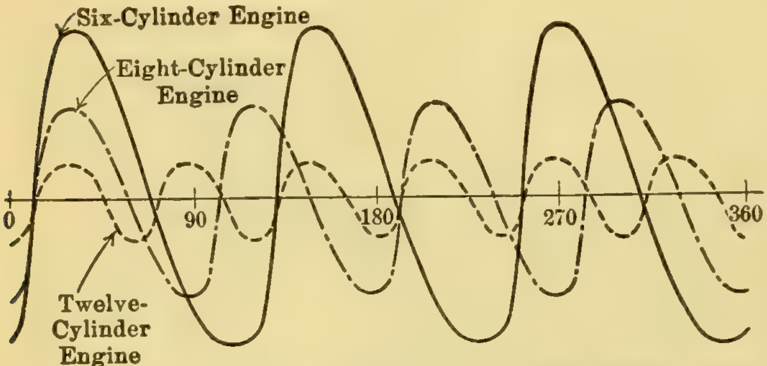
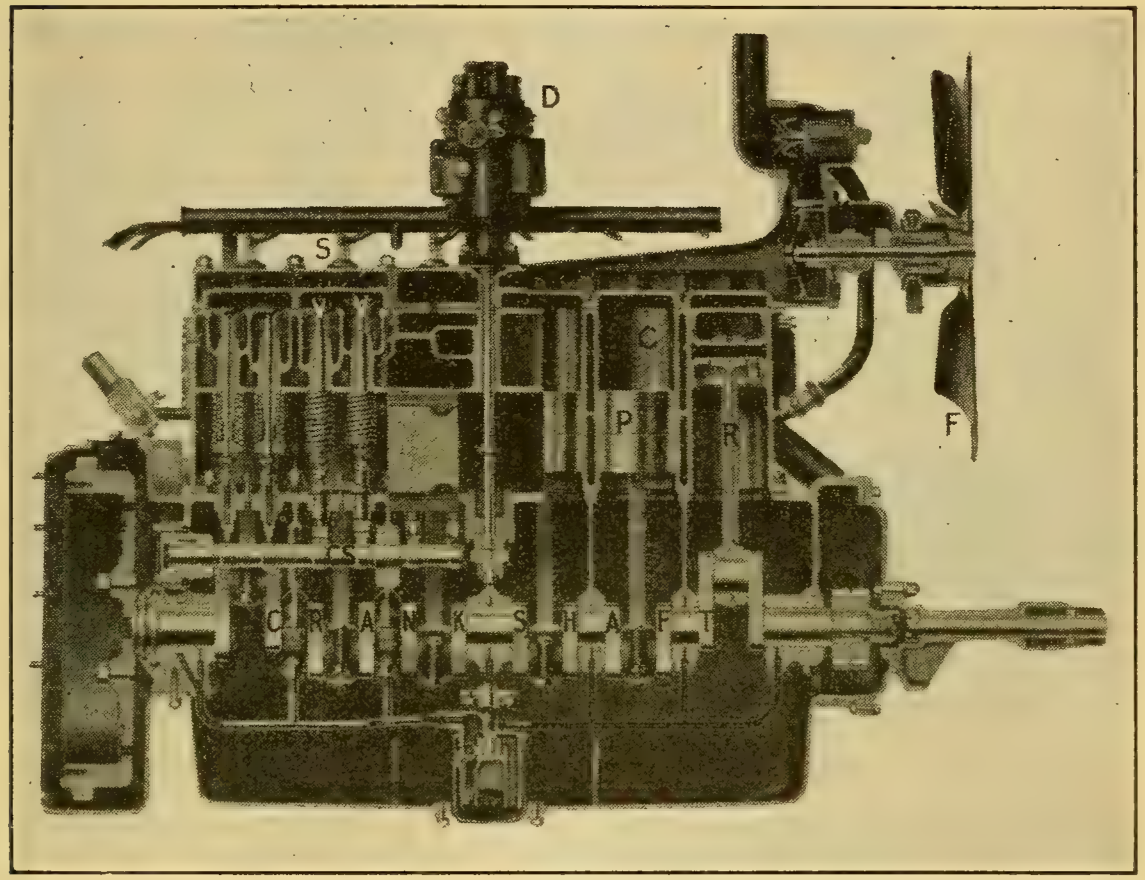


FIGURE 669. — POWER IMPULSES.

The greater the number of cylinders, the steadier the application of power. Distances above the line show the amount of power.

460. Gasoline Feed. — In the *gravity-feed system,* gasoline runs by gravity to the carburetor from a tank placed under the seat or in the cowl of the car. When the gasoline tank is placed on the frame at the rear of the car, another system has to be used. In the *vacuum-feed system* (Figure 671), a small auxiliary tank is mounted behind and above the engine and

connected by a pipe (1) with the main gasoline tank (*GT*) in the rear. This vacuum tank is divided into two chambers with an automatic valve between. A vacuum is created in the upper chamber on each intake stroke of the motor, and the ordinary air pressure on the gasoline in the main tank



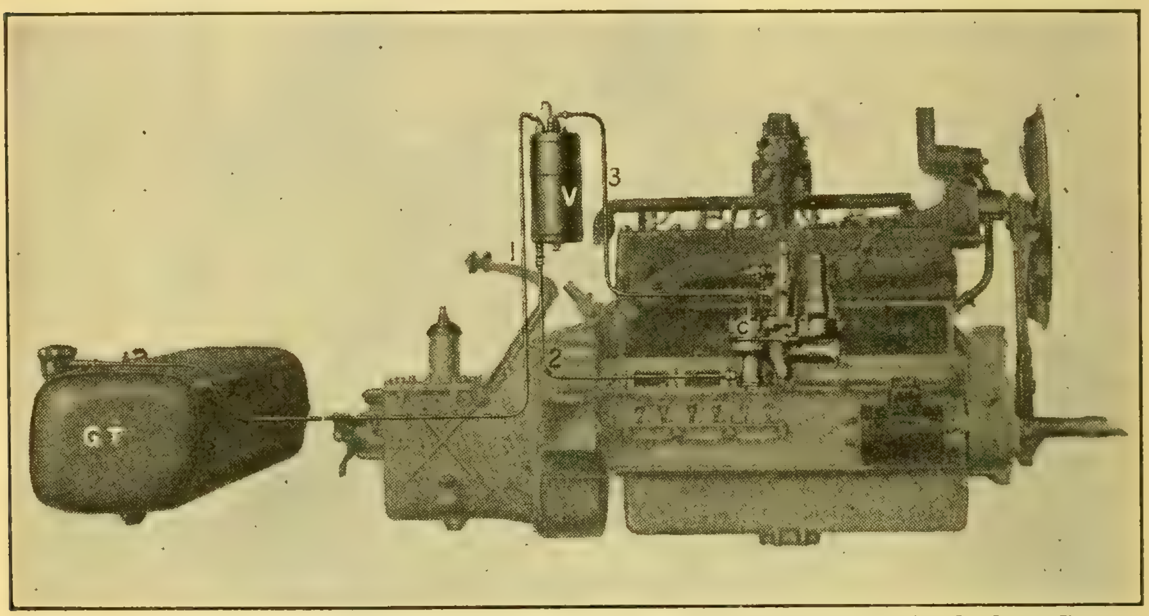
Courtesy of Packard Motor Car Co.

FIGURE 670. — SIX-CYLINDER ENGINE.

Sectioned through cylinders in front and through valves in rear. *C*, cylinder; *P*, piston; *CS*, cam shaft; *V*, *V*, valves; *S*, spark plug; *D*, distributer and timer; *F*, fan.

forces it through the delivery pipe to the upper chamber of the vacuum tank. When the gasoline has reached a certain height, a float valve shuts off the connection with the rear gas tank and opens a valve to the air, thus allowing the gasoline to flow into and fill the lower chamber. From this, the gasoline flows by gravity into the carburetor.

461. Carburetor. — The carburetor is a device to secure the vaporizing of the gasoline and its mixing with air in such proportions that a highly explosive and clean-burning mixture results. If there is too much air in the mixture (*lean mixture*), the explosion is weak and there is a lack of power. Too much gasoline for the air (*rich mixture*) results in an incomplete combustion, with waste of gasoline, and in deposit-



Courtesy of Packard Motor Car Co.

FIGURE 671. — VACUUM-FEED SYSTEM.

Pipe (3) connects the vacuum tank (*V*) to the intake manifold. Gasoline flows to the carburetor (*C*) through pipe (2).

ing carbon on the cylinder walls and the spark plugs. A good power-producing mixture contains about 1 part of gasoline to 15 parts of air by weight.

A needle valve controlled by a float in the gasoline chamber regulates the flow of gasoline into the carburetor (Figure 672). The usual carburetor is of the spray or nozzle type. In this form, the intake strokes of the engine produce a vacuum in the carburetor making the outside air rush through a constricted portion in the center of which is the gasoline nozzle. This rush of air entangles gasoline from the central nozzle,

giving a fine spray that vaporizes and mixes with the air. This main air supply is not sufficient when the load on the engine is heavy. Then atmospheric pressure opens an auxiliary air valve against the pressure of a spring and furnishes enough additional air to secure the complete combustion of the gasoline. An efficient carburetor has to be a complicated mechanism.

When an increase of speed or power is desired, a *throttle valve* located between the carburetor and the cylinders is opened by a lever on the steering wheel or by the toe accelerator. This increase in opening allows the engine to pump in more of the mixture of gas and air and consequently more power is obtained.

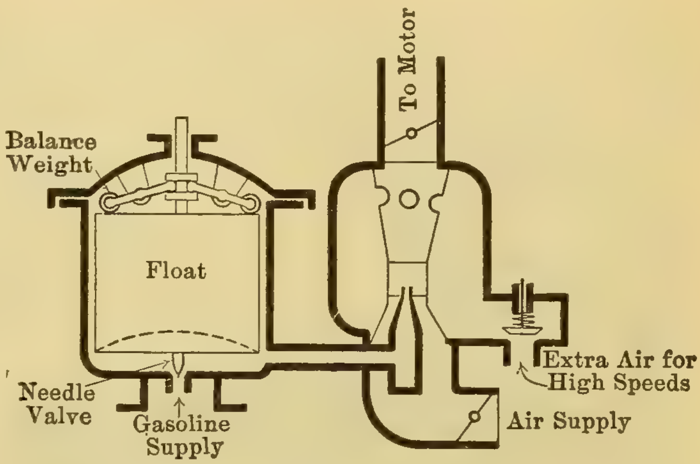


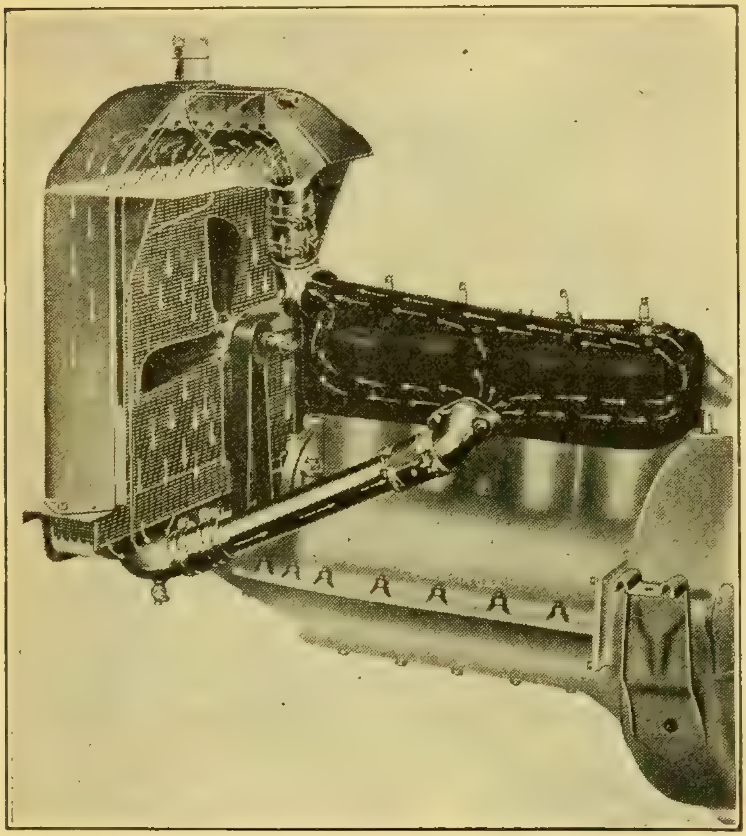
FIGURE 672. — DIAGRAM OF A CARBURETOR.

The throttle valve in the pipe leading to the motor, and the choke in the air supply are like the dampers in a stove pipe.

On the dash, there is a handle that operates the *choke valve;* this reduces the main air supply to the carburetor, producing a rich mixture for starting when the engine is cold.

From the carburetor, the gaseous mixture passes through the intake manifold to the cylinders. This manifold should be as short and smooth as possible. The exhaust manifold receives and carries off the burned gases from the cylinders. These two manifolds may be combined into a single pipe divided into an upper portion for the intake and a lower portion for the exhaust. The hot exhaust gases aid in the thorough vaporization of gasoline in the intake manifold as well as heating the mixture to a temperature suitable for its explosion.

462. Cooling System. — The cylinders become heated by the combustion of the gaseous mixture. Unless this heat is removed, the engine would become too hot for efficient operation and the cylinders might crack. The remedy is cooling by the circulation of water or air over the hot cylinder walls.



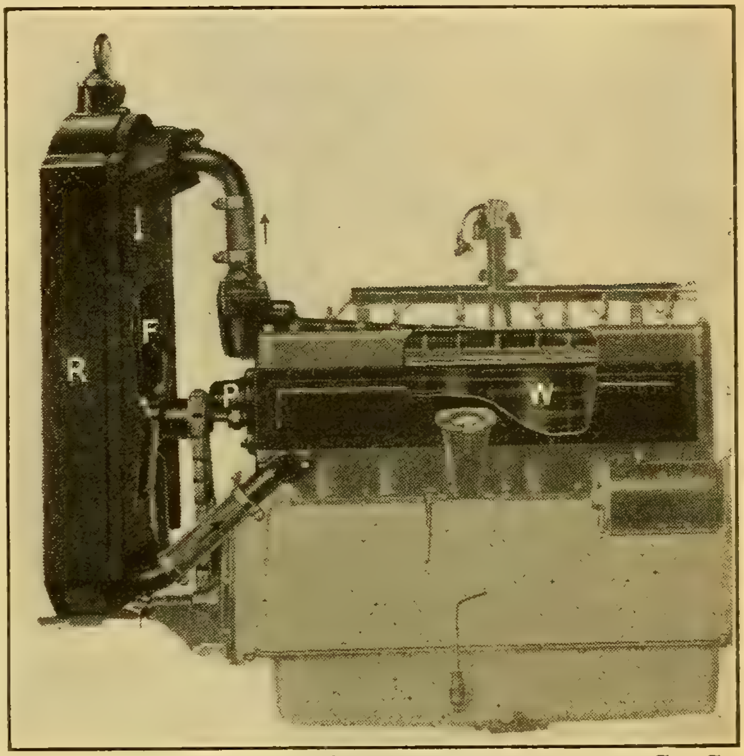
Courtesy of Ford Automobile Co.

FIGURE 673. — THERMOSIPHON SYSTEM.

Heating the water in the water jacket and cooling it in the radiator keeps the water circulating by convection.

The cylinders are usually incased in water jackets that furnish a space through which water circulates, receiving by conduction the heat developed in the cylinders. The circulation of the water is secured by a thermosiphon system or by a pump system. In the *thermosiphon system* (Figure 673), cold water from the radiator forces the hot water in the cylinder jackets to the top, whence it flows into the radiator for cooling again. As the water cools in the radiator, it sinks to the bottom. From there, it flows back in a convection current to the water jackets of the cylinders, entering at the bottom and ready for another circulation. This is like a hot-water heating system (§ 115). This system in a car does not operate unless the radiator is kept full to the level of the pipe from the water jackets.

A forced system of water circulation is far more efficient and is used in nearly all cars. It does not depend upon the temperature of the water in the water jackets and in the radiator. In the *pump system* of circulation (*P*, Figure 674), a centrifugal pump placed at the front of the engine and operated by it, forces water from cylinders to radiator and back again. The heated water from the tops of the cylinders flows slowly through very thin spaces between the double walls of the radiator (*R*), losing its heat to them by conduction. In turn, the metal of the radiator gives up its heat to the air in contact with it by radiation and conduction. To provide a sufficient supply of cooling air, a belt attached to the shaft of the engine runs a fan (*F*) that draws air through the radiator. In the better types of cars, a thermostatic regulator controls the flow of the circulating water according to the temperature of the season. To prevent too much cooling in winter, the radiator is partly covered. In air-cooled cars, a fan behind the engine draws air through passages between metal fins that extend along the outside of the cylinders.



Courtesy of Packard Motor Car Co.

FIGURE 674. — PUMP COOLING SYSTEM.

The wall of the water jacket is shown cut away at *W*. The pump drives the water from the top of the water jacket to the top of the radiator.

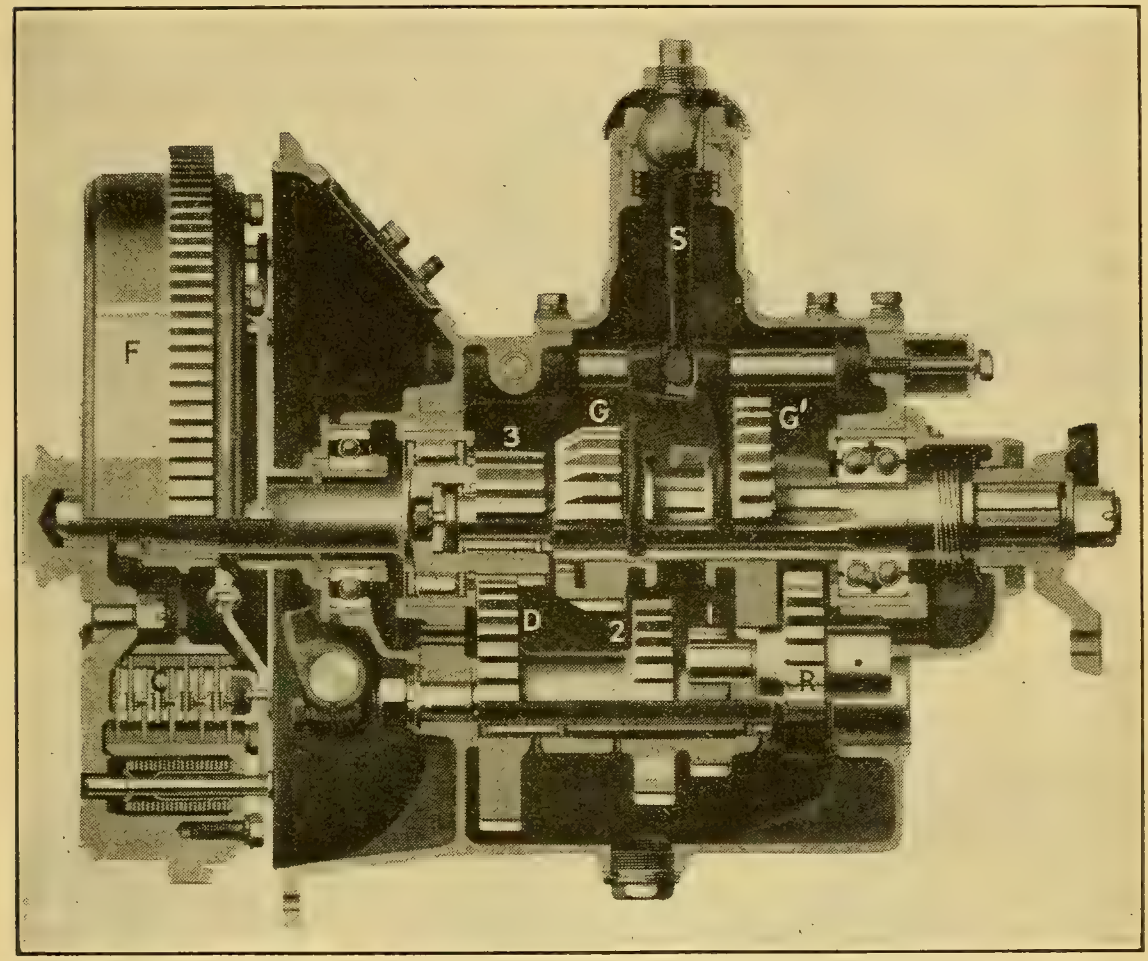
463. Clutch. — The pressure produced in the cylinders by the explosions of the gaseous mixture moves the pistons, and these in turn are connected to the *crank shaft* so as to rotate it. The clutch is a friction coupling for transmitting the rotary motion of the crank shaft to the main drive shaft. In the *cone type of clutch,* the inside face of the rim of the flywheel is hollowed out with a slight taper so as to receive a leather-faced metal cone. A strong spring holds the cone tightly against the flywheel, and the friction between the two transmits the motion of the engine to the rear wheels. When the foot pedal is pressed down, the clutch is disengaged from the flywheel. In the *disk type of clutch* (C, Figure 675), the friction of a number of parallel interlocking plates with alternate attachment to clutch shaft and flywheel provides for the transmission of rotation from crank shaft to flywheel.

An automobile engine must be set in motion by some external force before it can go through its regular cycle of operations to generate power. Hence it cannot start under load, and for this reason the clutch is disengaged from the flywheel until the engine is running smoothly. Then the clutch is gradually allowed to engage and the automobile moves along.

464. Gear Shifts and Transmission. — The crank shaft of the engine ends in a gear wheel that is always in constant mesh with a gear wheel on a counter-shaft (Figure 675). This counter-shaft has three fixed gear wheels (D, 2, 1), while the main drive shaft, which is beyond and in line with the engine, has two sliding gear wheels (G, G'). The position of these can be changed by means of a pair of gear shifter forks that the driver operates with the gear shift lever (S).

The counter-shaft with its gears regulates the force and speed that is passed from the engine to the main drive shaft.

In the *neutral* position of the gears, only the engine shaft and the counter-shaft are in gear. Then, if the engine is running and the clutch is in, the counter-shaft is rotated by the two gears in constant mesh (*D* and 3), but no power is being



Courtesy of Packard Motor Car Co.

FIGURE 675. — GEARS, FLYWHEEL, AND CLUTCH.

G′ and 1 engage in 1st speed; *G* and 2, in 2d speed; teeth inside *G* slide over 3 for high speed. *G′* and *R* engage for reverse. *S* shifts *G* and *G′*. *C* shows clutch in section. *F*, flywheel.

applied to the main drive shaft. The counter-shaft turns in the opposite direction to the engine shaft and more slowly, since there are more teeth in its meshed gear (*D*) than in the gear of the engine shaft (3). An automobile is put in neutral when one wants to test the action of the engine or when one wishes to "warm" the engine when it is cold on starting.

In first speed or *low,* the large sliding gear (G'), on the main drive is meshed with a smaller gear (1) on the counter-shaft. The engine must turn several times to the main drive's once, in this way reducing the speed of the main drive, but giving an increased mechanical advantage in that greater force is applied to the main drive. This is the condition desired when the inertia of the automobile must be overcome in starting.

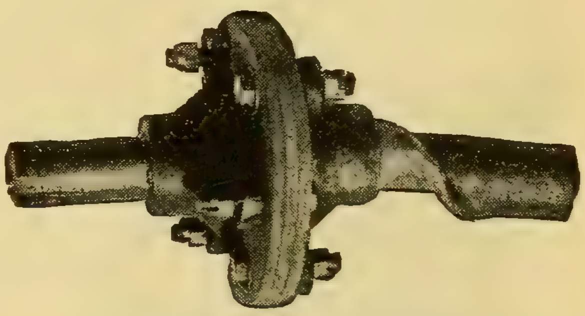
For the next or *second speed,* the other sliding gear on the main drive is engaged with a gear of equal size (2) on the counter-shaft. The main drive shaft then runs at the same speed as the counter-shaft but at a slower rate than the engine shaft. Second speed, as might be expected from its name, propels the automobile faster than *first.*

For third speed or *high,* the projections on the second sliding gear are meshed directly with projections of gears on the engine shaft, so that the main drive turns at the same rate as the engine shaft. The counter-shaft now rotates idly and is no longer regulating the speed of the main drive. When the automobile is being driven under ordinary conditions, it is in high. There is no occasion for shifting gears unless one desires to stop, reverse, or go up a hill.

In order to reverse, it is necessary to stop the car and then shift the gears into neutral. An additional gear, known as the *idler* gear (R), is used for reversing. This is in mesh constantly with a gear on the counter-shaft. G' is then shifted backwards to engage with R. The main drive and the counter-shaft ordinarily turn in opposite directions but this idler gear (R) makes them rotate in the same direction. The engine has not been reversed, but its power is now applied in making the car move backward.

465. Universal Joint. — The necessity for a flexible connection between transmission and differential arises from

the fact that they are not usually at the same level, and even if they were, the jolts and shocks of the road would displace them from even level if springs were used in the car. This flexible connection is secured by means of one or more universal joints; joints that transmit the rotating motion of the shaft but permit bending in any direction. Both ends of the drive shaft at the universal joint terminate in tough, elastic disks of fiber bolted solidly together (Figure 676). One part of the shaft must turn when the rest does but one end of the shaft may bend out of line with the other end without interfering with its effectiveness. In this manner, the power of the engine is transmitted through the main drive to a differential gear which turns the axle on each rear wheel.



Courtesy of Thermoid Rubber Co.

FIGURE 676. — FIBER DISK OF UNIVERSAL JOINT.

466. Differential. — The front wheels of an automobile, like those of a wagon, turn freely on their axles. The axles of the rear wheels are fastened firmly to them, since the driving power of the engines is transmitted to the wheels through these axles. When the car turns a corner, or goes over an uneven road, the two rear wheels pass over unequal distances, and one wheel would drag over the road, wearing out the tire, if the parts of the rear axle were rigidly connected. This undesirable state of affairs has been overcome by a combination of gear wheels, called the *differential*. To understand this, let us study a simplified model of the differential, shown in Figure 677. The crank corresponds to the engine; as it turns, the driving pinion, P, rotates the large ring gear, R. Mounted on axles that are connected to the mounting of

the ring gear and turn with it, are differential pinions, *G, G*. The teeth of these pinions are engaged at all times with the teeth of a differential gear on each side, *D, D*, and the pinions are entirely free to rotate on their own axles. Since the two differential gears face in opposite directions, and so tend to turn the differential pinions in opposite directions, these pinions do not turn at all as long as the car moves evenly straight ahead, but serve to lock the two gears together, and to transmit to them the motion of the ring gear. Each of the differential gears, *D, D*, is mounted on one end of a half axle, which drives the rear wheel attached to the other end. Now, if the car turns, so one wheel must travel farther than the other, its differential gear can travel faster than the gear of the other wheel, by rotating the pinion on its axle. An intelligent fly imprisoned in the case that surrounds the differential mechanism could learn much about relative motion (relativity) by observing the action there when a car is turning. The shaft of the drive pinion, the

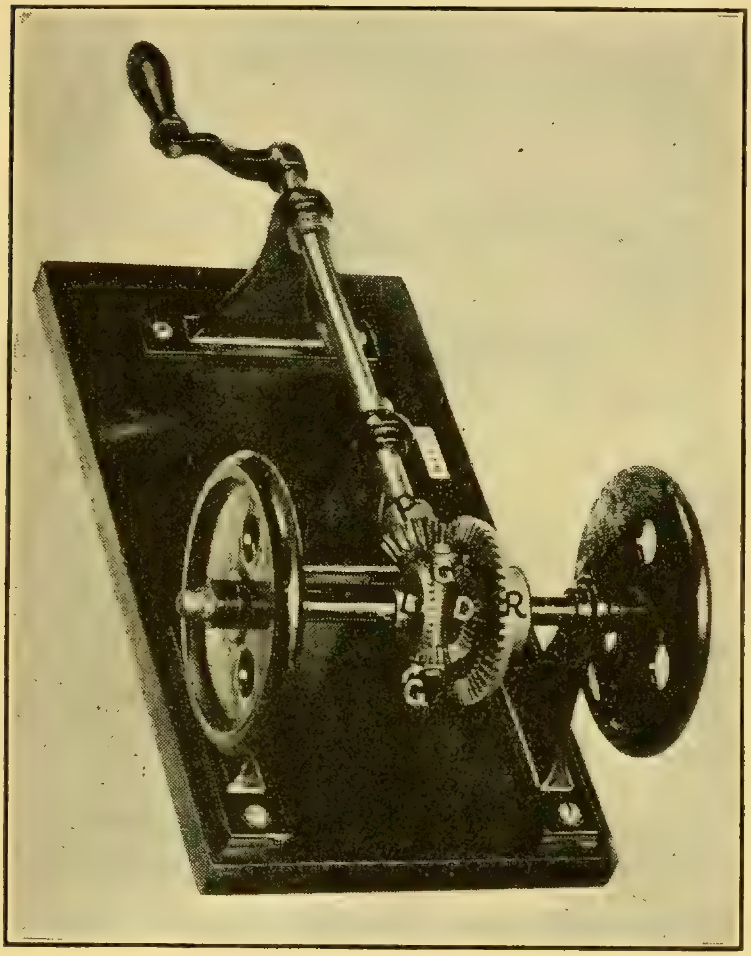
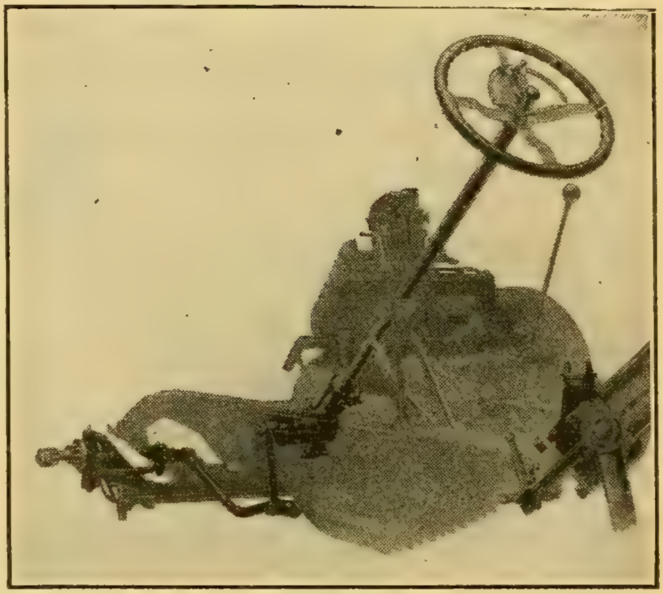


FIGURE 677. — MODEL OF DIFFERENTIAL.

P, driving pinion; *G, G*, differential pinions, mounted on ring gear, *R*, turn differential gears, *D, D*, which drive the wheels.

ring-gear mounting, and the two differential gears, each turns independently in roller bearings, and the whole mechanism runs in grease or heavy oil for lubrication.

467. Steering Gear. — The steering gear of an automobile is an excellent example of a compound machine, including a combination of wheel and axle, levers, and either gears or screw. The large steering wheel has as the corresponding axle the lower end of the steering post. In one simple and efficient steering gear (Figure 678), the steering post terminates in a screw, the nut of which sets in motion a series of bent levers, which turn the short axle of the wheel on the driver's side directly; the axle of the other wheel is connected with this by a tie rod. The steering wheel and post have a large positive mechanical advantage; at some points in the mechanism, force is sacrificed to gain distance. But, considering the entire complex machine, from steering wheel to tire, we know that the mechanical advantage is more than one, because the hand on the steering wheel moves a much greater distance than the front wheel turns.



Courtesy of Packard Motor Car Co.

FIGURE 678. — STEERING GEAR.

The shaft of the steering wheel moves a set of bent levers by means of a split nut shown enlarged at the bottom right.

468. Electrical System. — The electric system of a modern automobile is in many respects like that of a small town. In the early days of the auto, the only use of electricity was

for the ignition of the mixture in the cylinders. Now, an electric motor cranks the car at starting, electric lights are used to illuminate the road and to warn the car behind, an electric heater warms the mixture in the carburetor and another may light the driver's cigar, and an electrically driven wiper keeps the windshield clear when it rains.

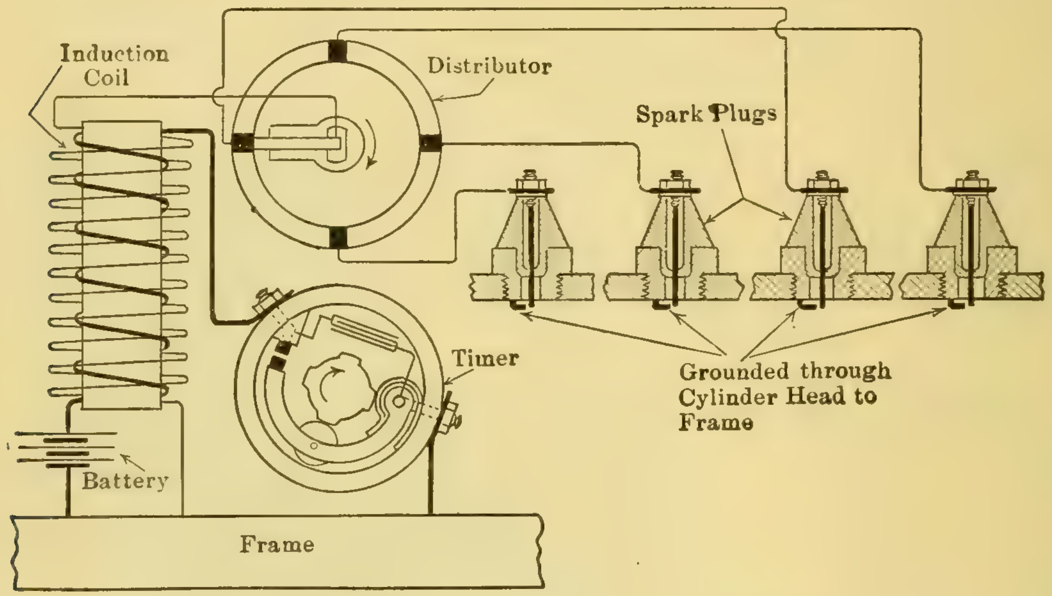


FIGURE 679.—AUTOMOBILE IGNITION SYSTEM.

The rotating parts of the timer and the distributer, shown with arrows, are mounted on the same shaft. The primary circuit is broken by the timer and the distributer connects the proper spark-plug to the secondary.

The power house of the car includes a low-voltage generator, driven by the engine, and a 6- or 12-volt storage battery, to furnish current for starting and for operating the electrical accessories when the engine is not running. The battery and generator are connected in parallel, through a relay, which prevents the battery from discharging through the generator, but permits the generator to charge the battery when the car is running. The similarity to a power-house storage battery will be perceived. One widely used make of car employs a low-voltage magneto (§ 314) both for lighting and ignition, while many make use of a high-voltage mag-

neto as an alternative to the battery and induction coil in the ignition system.

The usual ignition system employs an induction coil, whose primary is connected to the battery through an interrupter (Figure 679) driven by the engine shaft. The secondary is connected to a rotating distributer switch, on the same shaft as the interrupter or *timer*. The mounting is such that when the primary circuit is broken by the interrupter, the distributer switch is in contact with the line leading to the cylinder that should fire at that particular instant; so a high voltage impulse is sent to the spark plug in that cylinder, and a spark passes across the spark gap and ignites the mixture surrounding it. A lever on the steering post controls the point at which the interrupter breaks the circuit relative to the position of the piston in the cylinder, "advancing" or "retarding" the spark. The primary current returns to the battery, and the secondary current to the induction coil, through the frame of the car, as one end of each electric circuit in the car is attached to the frame, or "grounded." This greatly reduces the amount of wiring necessary.

The horn usually has a diaphragm set into vibration by being struck by the projections on the shaft of a small motor. A push button, conveniently located for the driver, controls the motor horn, and other switches turn the current on and off from the ignition, lighting, and starting systems.

SUMMARY

The **frame** of the automobile is of strongly braced steel. The chassis consists of frame, wheels and axles, and power plant.

Springs are employed to protect the body and load from the roughness of the road. Pneumatic tires and shock-absorbers supplement the springs.

Automobile bearings are of the ball or roller type, except for the crankshaft and springs. The bearings are lubricated with oil or grease to reduce friction and wear.

Brakes employ friction to check the motion of the car. They usually act on drums on the rear wheels, but brakes on the drive shaft or on the front wheels are also sometimes used.

The **power plant** is usually a gasoline engine having from 4 to 12 cylinders. The larger the number of cylinders, the more even the application of power.

The **carburetor** vaporizes the gasoline, and mixes it with a proper proportion of air. The mixture is usually heated before being admitted to the cylinders.

Excess heat generated in the engine **is removed** by directly cooling with air, or by being carried by water circulating through double walls of the cylinders to the radiator, where the water is air-cooled.

The **clutch** serves to connect the engine to the shaft driving the rear wheels, or to disconnect it.

The **transmission gears** enable the drive shaft to turn at speeds less than the engine shaft when more power is desired.

Universal joints permit an angle between the engine shaft and the transmission shaft.

The **differential** (*a*) delivers power from the drive shaft to the axles of the rear wheels, and (*b*) permits each wheel to turn independently of the other.

The car is steered by a wheel connected by a series of levers to the front wheels.

The **electrical system** includes a storage battery and generator for starting and lighting, and an induction coil for producing the high voltage necessary for ignition. A magneto may be used instead of the battery and induction coil (high-tension) or instead of the generator (low-tension).

EXERCISES

1. Mention two important features in the construction of an automobile frame, and give the reason for each.

2. A driver takes a heavy friend to ride in a five-passenger car. Will the load on the tires be more even, if the passenger sits beside the driver, or if he sits in the rear seat? Explain your answer, using the principle of moments.

3. A car has a 116-inch wheelbase. The engine weighs 500 lbs and its center of gravity is 18 inches back of the front wheels; the front axle weighs 75 lbs, the rear axle 150 lbs; each wheel weighs 30 lbs and the remainder of the chassis and body weighs 1500 lbs, and has its center of gravity 70 inches back of the front wheels. Calculate the load to be supported by each tire.

4. Mention three applications of elasticity in the automobile. Why does the car continue to bounce several times after passing over a bump?

5. How is the principle of moments applied to reduce the force on the springs at the end of the torque arm?

6. Write a brief paragraph on the advantages and disadvantages of friction in the automobile.

7. If the brakes of a car going 20 miles an hour will stop it in 45 feet, in what distance will they stop the car if it is going 40 miles per hour? (Hint: Consider the kinetic energy in the two cases.)

8. Explain the use of the engine as a brake. Will it be more effective "in high" or "in first"? Explain.

9. What is the power plant of an automobile and what does it accomplish?

10. Why was the old one-cylinder automobile jerky in its operation? Explain the advantage gained in increasing the number of cylinders.

11. How many cylinders must fire while the crankshaft is making two revolutions? How does the number of power impulses applied to the crank shaft depend upon the number of the cylinders? What advantage has an eight-cylinder car over a four-cylinder one? What disadvantage is there?

12. How are valves of a multicylinder engine operated? How is proper timing secured? Why are not the cylinders fired in the order in which they are arranged on the engine block?

13. Trace the course of the gasoline in the *gravity-feed system.* Name a car that uses it.

14. Name and locate the two tanks in the *vacuum-feed system.* Describe the construction of the vacuum tank. What produces the vacuum in it and what makes the gasoline flow into it? Explain how the gasoline gets from the vacuum tank to the carburetor.

15. Define a *carburetor.* Distinguish between a *lean mixture* and a *rich mixture.* How can you tell when the mixture is too rich?

16. Make a labeled drawing of a carburetor. Explain how the mixture of air and gasoline is obtained. How is the air supply increased when the load on the engine is heavy?

17. Where is the *throttle valve?* How is it operated? When? What happens when it is opened?

18. What is reduced by the *choke valve?* When is it used?

19. Describe the construction and operation of the *intake* and the *exhaust manifolds.*

20. Why is a cooling system necessary for an automobile?

21. Make a diagram of the *thermosiphon* system of cooling, indicating by arrows the course of the water. What disadvantage has this system?

22. In the *pump system* of circulation, how is the water cooled? How is the radiator cooled? State the parts played by conduction and radiation in these two processes?

23. How are the cylinders cooled in such cars as the Franklin?

24. What is the *clutch* and what does it do? Describe one type of clutch? Why is the clutch released before the car is started?

25. In what does the crank shaft end? What two gear wheels are always in constant mesh? On what shaft are the three fixed gear wheels? The two sliding gear wheels? What changes the position of the sliding gears?

26. What is the object of the counter-shaft and its gears?

27. What is in gear "in neutral"? Compare the direction and relative speed of rotation of the engine shaft and the counter-shaft when the clutch is in and the car is in neutral. When is an automobile put in neutral?

28. For each of the following speeds, state (*a*) what is in mesh, (*b*) what is rotating and at what relative speeds, and (*c*) when and why the speed is used: *low, second,* and *high.*

29. What striking difference is there between a locomotive and an automobile engine in the matter of reversing?

30. What is the first thing to do before reversing an automobile? Where is the *idler gear* and how does it bring about the reversing of a car?

31. When would you shift from low into second? From second into high? From high into low? Why should the shifting of gears be done with a slow even motion?

32. State the object, construction, and operation of the universal joint.

33. Explain briefly why a differential is necessary in an automobile and not in a wagon.

34. Describe the motion of the differential pinions (*a*) when going straight ahead, (*b*) when turning a corner. Explain the first case.

35. Which is better, a large or a small steering wheel? Why?

36. When a front tire is nearly flat, it is more difficult to steer the car. Explain.

37. Give three uses of the storage battery in an automobile.

38. Why is it not usually necessary to remove the storage battery from a gasoline automobile for charging, while it is necessary in a car run by storage batteries?

39. Why do automobilists on a long trip frequently keep their lights burning during the daytime?

40. In the ignition system, explain the use of the coil, the timer, and the distributer.

41. Explain the advantage of using a "single-wire" or "grounded" electric system in an automobile.

42. Explain what is taking place when the battery indicator on the dash reads "charge" and when it reads "discharge."

CHAPTER XXXVI

VACUUM TUBES AND RADIO COMMUNICATION

469. Conduction of Electricity through Gases. — We have already seen that an electric current in a solid conductor consists of a stream of electrons; in liquids there is a motion of + and − ions in opposite directions, which results in electron's being transported from the cathode to the anode. Dry air is a very poor conductor for currents of ordinary voltage, because it contains few electrons that are free to escape

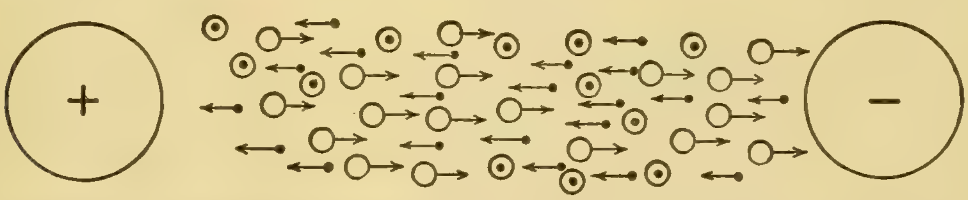


FIGURE 680. — The large circles represent terminals of the induction coil. Dots stand for electrons, and circles for positively charged particles. A dot surrounded by a circle indicates an atom that is not ionized.

from the nucleus of the atom to which each belongs. There are, however, always some free electrons in the air, as a result of the action of radio-active substances in the earth and of ultra-violet light from the sun. It is evident that if means are found to increase the number of free electrons, by separating them from neutral atoms and leaving the latter positive, we shall have a gas *ionized*. An ionized gas will contain free negative particles (electrons) and free positive particles (atoms from which an electron has been driven).

If the positive and negative terminals of an induction coil are placed in such an ionized gas, the electrons will stream

toward the + plate and the positively charged particles toward the − plate (Figure 680). These streams of ions will constitute an electric current, just as similar streams do in an ionized electrolyte. This effect is secured only when the voltage between the plates is very high.

The reason that a high voltage is necessary seems to be that such a high voltage will give the few electrons present at the beginning sufficient energy to drive other electrons out of some of the neutral atoms with which they collide. The positively charged ions also may knock electrons out of neutral atoms, or out of the cathode plate.

470. Lightning. — The air is always ionized to some extent, and both electrons and positively charged atoms form centers or nuclei around which water vapor condenses into droplets. Clouds, therefore, may be either positively or negatively charged. When two oppositely charged clouds approach each other, or when a highly charged cloud induces a sufficient opposite charge on another nearby cloud, or upon the earth, a discharge may take place suddenly between the two oppositely charged bodies. This discharge is *lightning*, and differs only in intensity from the discharge of a Leyden jar or that between the terminals of an electric machine or an induction coil. Since the intensity of the charge is greatest on *points*, objects projecting from the earth, such as tall trees, steeples, and high buildings, are likely to form discharge points, and so to be "struck by lightning." The sudden passing of the lightning flash, usually lasting less than a millionth of a second, heats and enormously expands the air in its path. Into the partial vacuum thus formed, the air rushes back violently, causing *thunder*. The fact that light travels so much more rapidly than sound is the reason why we see the lightning before we hear the thunder.

471. Geissler Tubes. — When the gas we are seeking to ionize is at atmospheric pressure, its atoms are so crowded that an electron can move only a short distance before collision with some atom. The result is that the electron rarely gains sufficient velocity between collisions to ionize the atom that it strikes. By inclosing the gas in a tube provided with electrodes and connecting the tube to an air pump, a large proportion of the gaseous atoms may be removed by the pump. The remaining atoms are so much farther separated that an electron gets much greater velocity before it collides with an atom, and therefore strikes the atom with much greater kinetic energy.

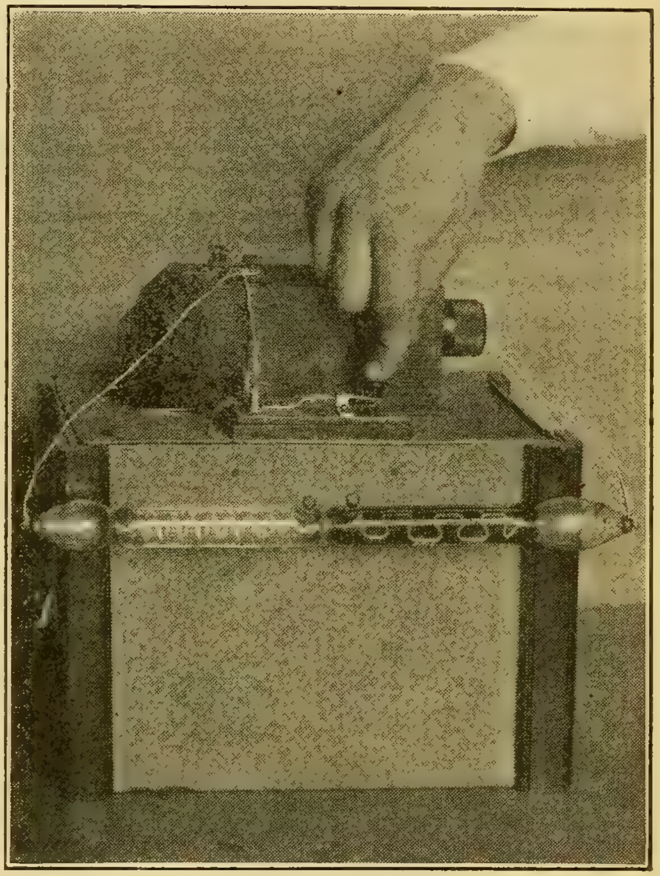


FIGURE 681. — GEISSLER TUBE IN ACTION.

An automobile induction coil is discharging through the tube. The much bent center of the tube is surrounded by liquids that glow from its action.

Such a partially exhausted tube containing less than $\frac{1}{300}$ of the original gas is called a *Geissler tube* (Figure 681). An induction coil that would give only a quarter-inch spark between its terminals in air may cause a quiet discharge through a Geissler tube a foot or more long. When the current is passing, very beautiful luminous effects are seen within the tube. The color and the character of the glow depend on the gas in the tube, the glass of which

it is made, and the voltage applied to it by the induction coil. A dark space always surrounds the cathode, and sometimes there is another dark space further on in the tube, but a glow extends from the anode through the greater part of the length of the tube. This glow is often interrupted by dark spots (Figure 682). If the discharge takes place in the open air, a spark results from the impact of the electrons, driven by the exceedingly high voltage of the plates. The dazzling light of the spark is the result of the disturbance produced within the atoms by this impact.

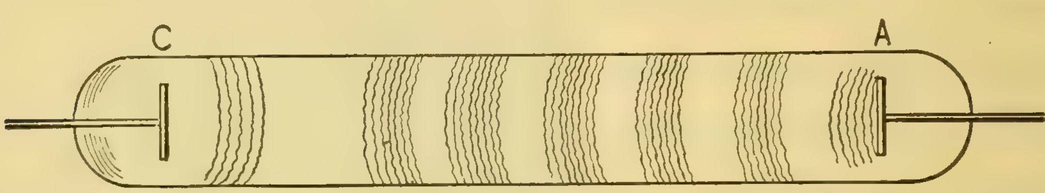
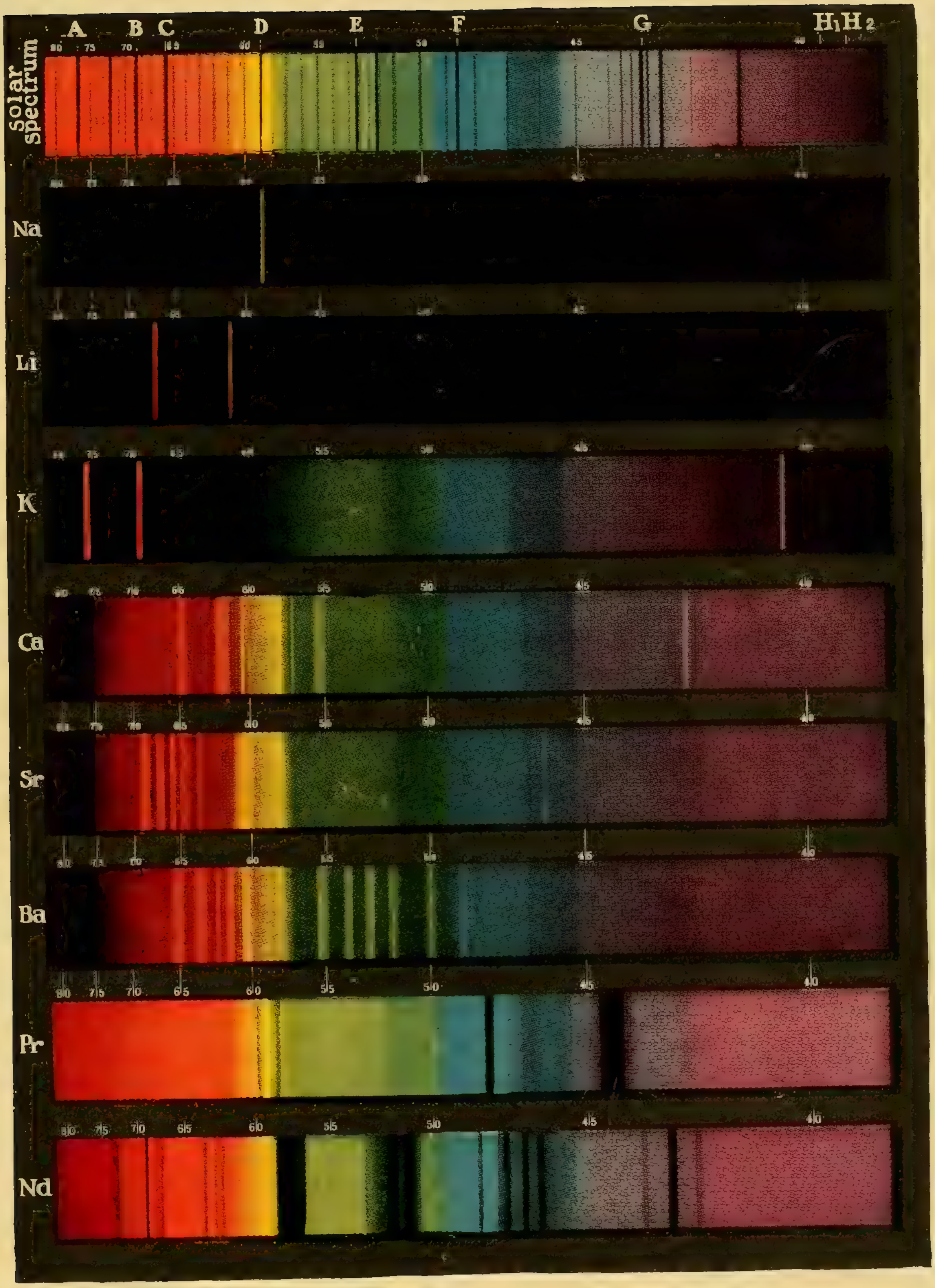


FIGURE 682. — GEISSLER TUBE DISCHARGE.

A is the anode; *C*, the cathode. There are bands of light where shading appears in the drawing; the rest of the tube is dark.

The softer glow of the Geissler tubes is also due to disturbances within the atoms and is accompanied by a rapid liberation of electrons.

472. X-Rays. — As more and more air is pumped out of the tube, after a time the glow diminishes. When only about one millionth of the gas remains, the glow disappears entirely, because there are relatively so few atoms left that they are rarely struck by the electrons. Such tubes are called *Crookes tubes* (Figure 683), from their discoverer, Sir William Crookes. When the electrons in a Crookes tube strike the glass or an obstacle placed in their path, electromagnetic waves, which may be only $\frac{1}{30,000}$ as long as light waves, result from the violent impact of the electrons. These exceedingly short waves are the X-rays discovered by Roentgen. Let us discuss their properties first and then X-ray tubes and their uses.



VARIOUS SPECTRA

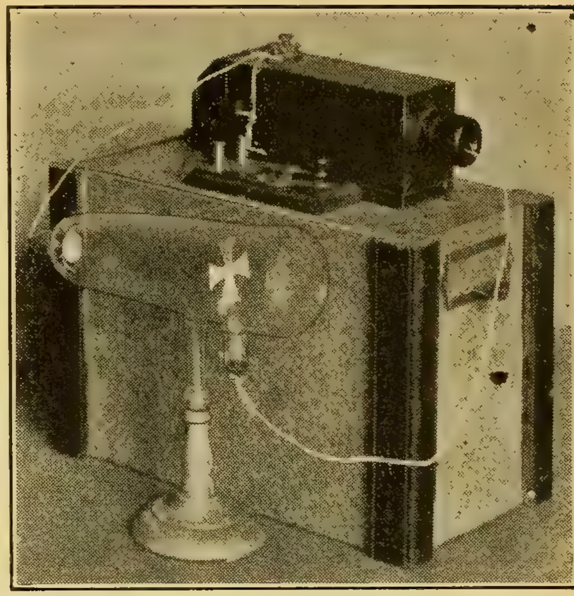


FIGURE 683. — CROOKES TUBE.

Electrons from the cathode at the left are intercepted by the aluminum cross, which casts a shadow on the illuminated right end of the tube.

Many substances that are opaque to light, such as wood, hard rubber, black paper, and aluminum, are transparent to X-rays in varying degrees. Dense substances, like lead, let X-rays pass only to a small extent. Glass is much less transparent to X-rays than to light; lead glass is decidedly opaque to them. X-rays are entirely invisible, but they can be detected by their action on photographic plates, which they affect more than light does. They also cause many materials on which they fall to glow, or *fluoresce.* Screens coated with such a substance, as barium platinocyanide, are used to detect them. X-rays are powerful in ionizing gases.

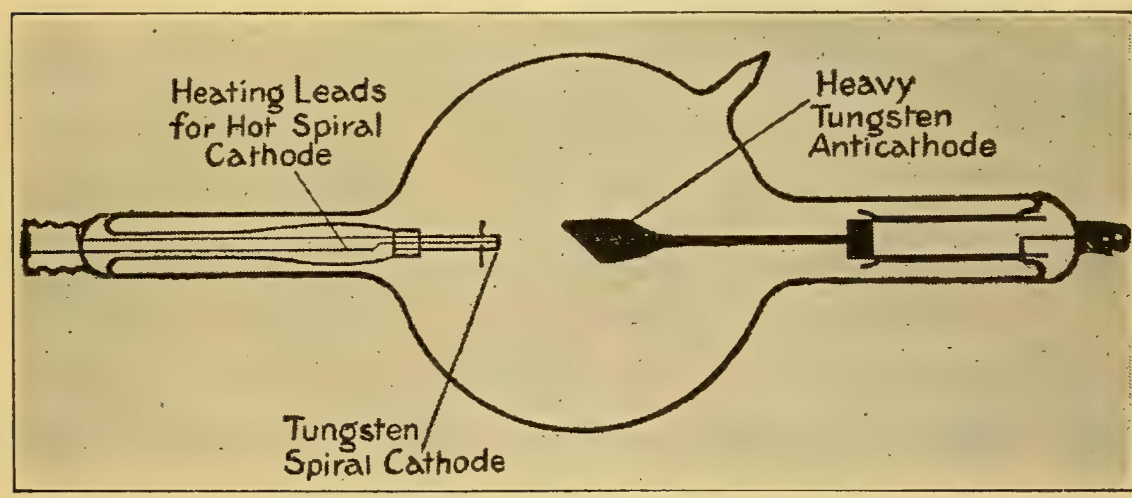


FIGURE 684. — COOLIDGE X-RAY TUBE.

The cathode is a coil of tungsten wire heated by an electric current. High voltage causes the electrons to strike the anti-cathode, from which great quantities of X-rays radiate.

They produce serious burns if the flesh is exposed to them for any considerable length of time.

473. X-Ray Tubes. — In the earlier forms of X-ray tubes, electrons driven from the concave surface of the cathode of a Crookes tube were allowed to focus on a heavy metal plate, placed in the center of the tube at an angle of 45° to the cathode stream. The violent bombardment of the electrons on this small area gave rise to X-rays that streamed out from this point in all directions. Some were intercepted by the glass, but many passed through, if the right kind of glass were used. In the modern Coolidge tube (Figure 684), the vacuum is about a billionth of an atmosphere. The electrons are emitted by a cathode consisting of a coil of tungsten wire, electrically heated. High voltage drives these electrons across to an inclined heavy anticathode of tungsten, and as the electrons strike this target with enormous velocity, it becomes a powerful source of X-rays of high frequency.

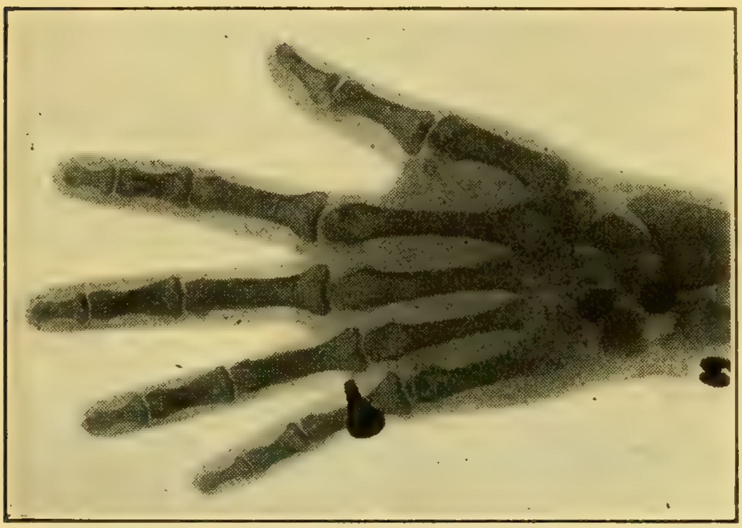
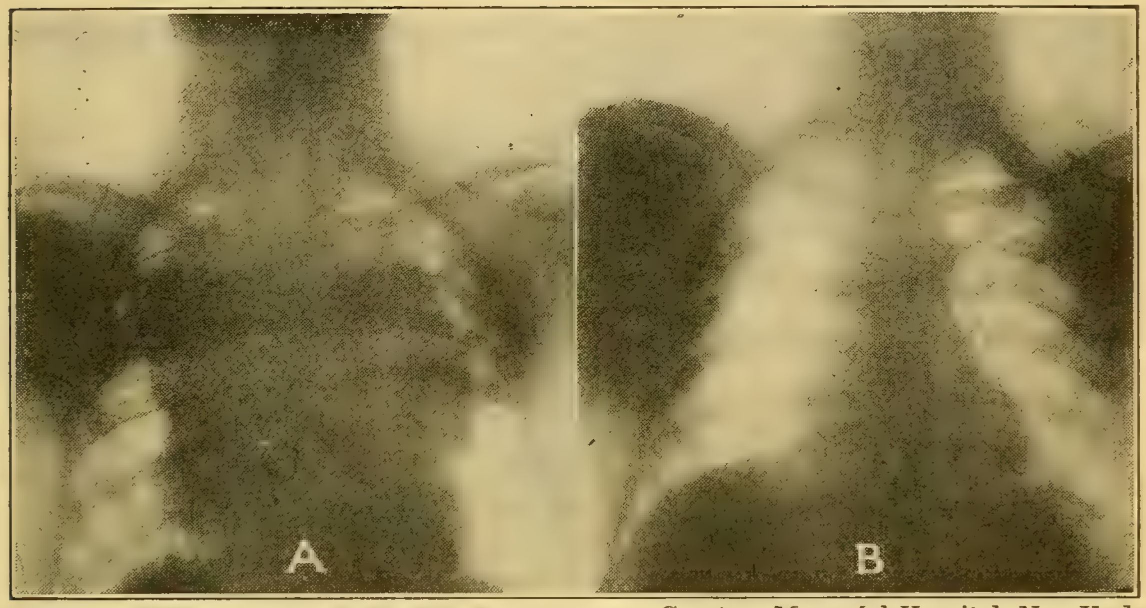


FIGURE 685. — X-RAY PICTURE OF HAND.
The dark spots are a ring, a cuff button, and two sleeve buttons.

474. Uses of X-Rays. — The earliest, and still the most important, use of X-rays is for the examination of the human body. The bones and the denser tissues of the body are more opaque to the X-rays than the muscles are. Hence when a part of the body is placed between the X-ray tube and a

photographic plate or a fluorescent screen, the shadows of the bones are much darker than those of the flesh (Figure 685). This makes it possible to study fractures, and to locate any foreign body, such as a bullet or a needle, that may have lodged in the body. The thickening of the lung tissue by tuberculosis can be readily seen in an X-ray picture. The location and extent of a tumor may be revealed (Fig-



Courtesy Memorial Hospital, New York.

FIGURE 686. — X-RAYS IN DISEASE.

A, Tumor in the chest, showing as a large dark blotch. *B*. Same patient after several months of X-ray treatment, with the tumor almost entirely gone. The dark spot still showing behind the ribs is the heart.

ure 686). The beating of the heart may be watched on the fluorescent screen, and by mixing a harmless salt of one of the heavy metals with food, the entire movement of the digestive system may be studied. Teeth are examined by X-rays for cavities and ulceration. Other uses of X-rays include detecting hidden flaws in metals, distinguishing true gems from imitations, the location of pearls in oysters, and the detection of articles hidden for smuggling. X-ray treatment is being used for cancer and other malignant growths and for

sterilizing various food products. In the realm of pure physics, X-rays have revealed much concerning the structure of crystals, and the results of these investigations have yielded much light on the structure of matter.

QUESTIONS

1. How is an electric current conducted through a wire? Through an electrolyte?

2. What is an ionized gas? State one way by which the ionization may be increased.

3. State the conditions necessary for the conduction of electricity through air and explain how this conduction takes place.

4. How does the action of electrons in a Geissler tube differ from conduction in free air?

5. Name three conditions that affect the appearance of a Geissler tube discharge.

6. Make a labeled drawing of a simple form of X-ray tube.

7. How are X-rays produced and what is their nature?

8. Compare several substances with reference to their transparency to X-rays.

9. State two ways by which X-rays may be detected.

10. Name four important uses of X-rays.

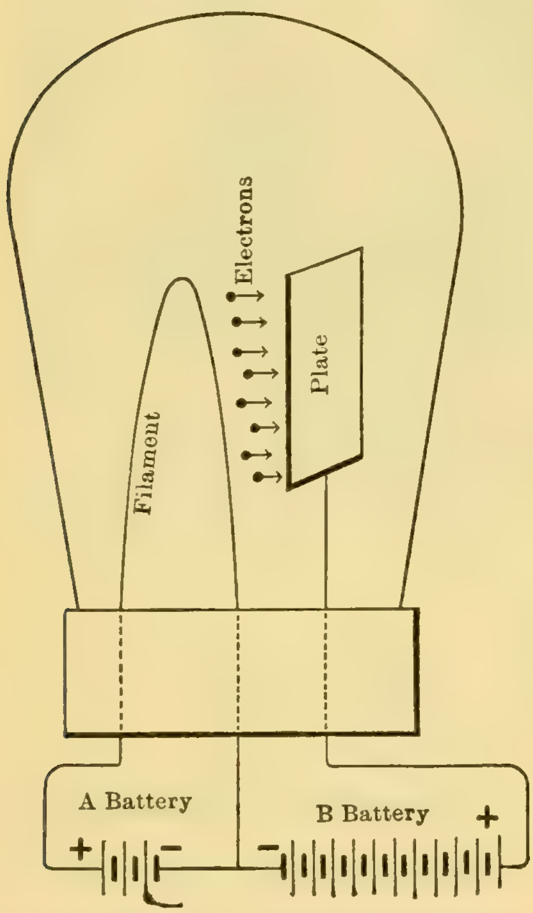
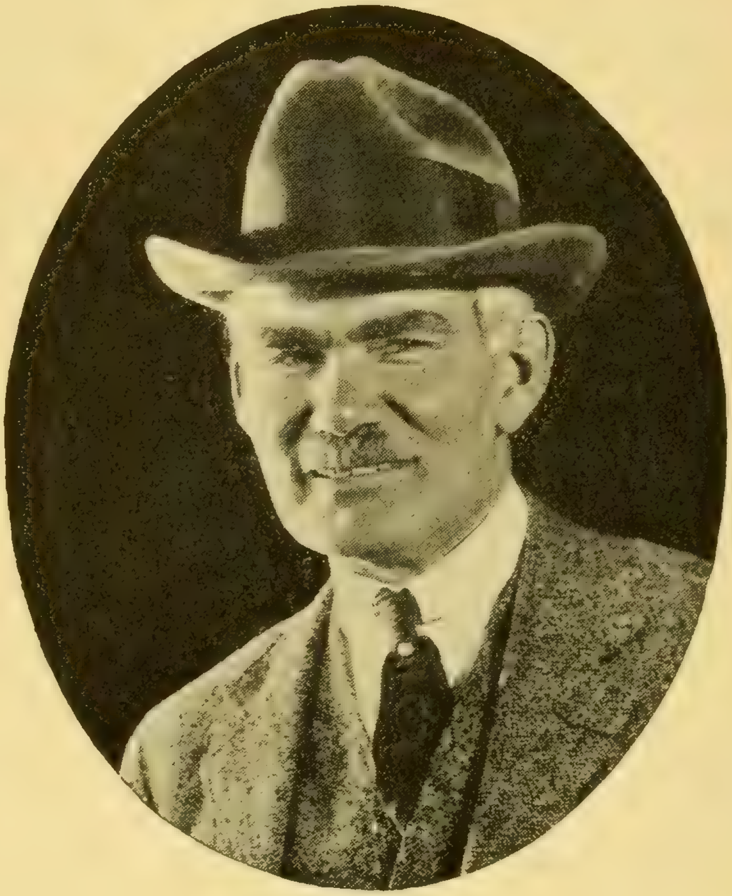


FIGURE 687. — FLEMING VALVE.

The A battery heats the filament, causing it to emit electrons. The B battery keeps the plate positive, so that it attracts the electrons.

475. Electron Valves. — Edison noticed many years ago that a negative electric discharge passes from the filament of an incandescent lamp to an electrode placed in the bulb. We now explain this by saying



Lee De Forest (1873–). The widespread interest in radiotelephony has made De Forest almost a household word. The third element in the audion bulb was inserted as the result of De Forest's researches, and it is this grid that makes the accurate reception of radio waves possible. Science progresses when discovery of great principles is attended by careful experimentation with patiently devised apparatus. De Forest has extended the range of science by making valuable researches and practical applications of scientific principles.

that the heated filament gives off electrons. If the filament and electrode are connected to the terminals of a battery, a stream of electrons will flow when the plate is made positive, but no current will pass if the plate is made negative. This combination of plate and glowing filament in a vacuum tube constitutes Fleming's vacuum valve (Figure 687). De Forest inserted a grid of metal wires between the plate and filament (Figure 688), giving us the three-electrode valve, now so widely used in radio and telephone work. The grid, like the plate and filament, is connected to a terminal outside the tube (Figure 689).

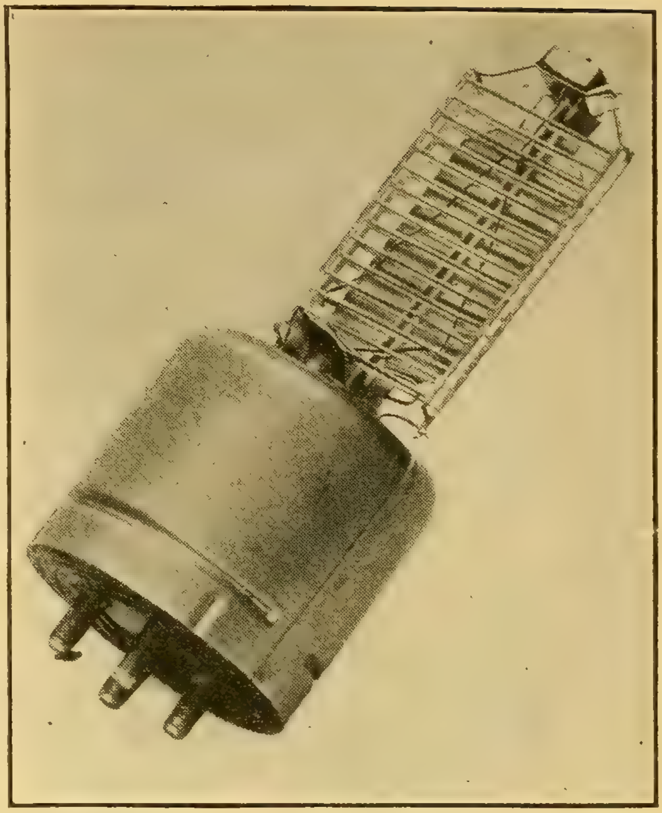


FIGURE 688. — GRID, PLATE, AND FILAMENT

The glass tube and the front half of the plate have been removed. The filament is a single loop of wire, showing between the two ladder-shaped halves of the grid. Half of the plate is seen at the back.

When the grid is made +, it attracts electrons that have been emitted from the filament and so causes the electrons to leave the filament in greater numbers. These electrons are also attracted by the + plate, and, since the fine wires

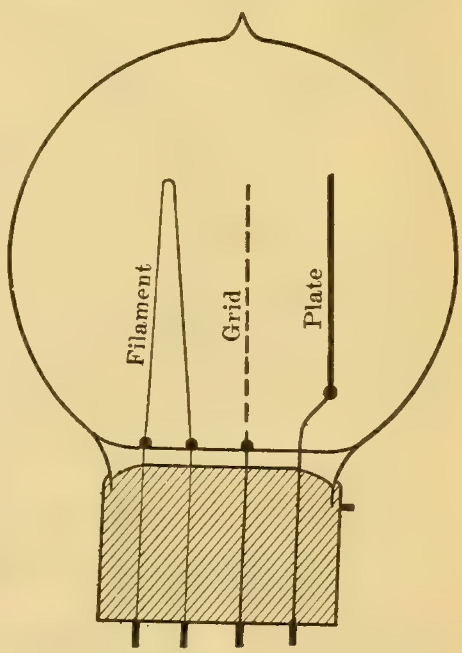


FIGURE 689. — THREE-ELECTRODE TUBE OR AUDION. Diagram shows terminals.

of the grid intercept only a few of them, the stream between the filament and plate is greatly increased (Figure 690). Thus more current flows through the external circuit connecting the plate with the filament. *A positive grid, then, increases the current in the plate circuit.*

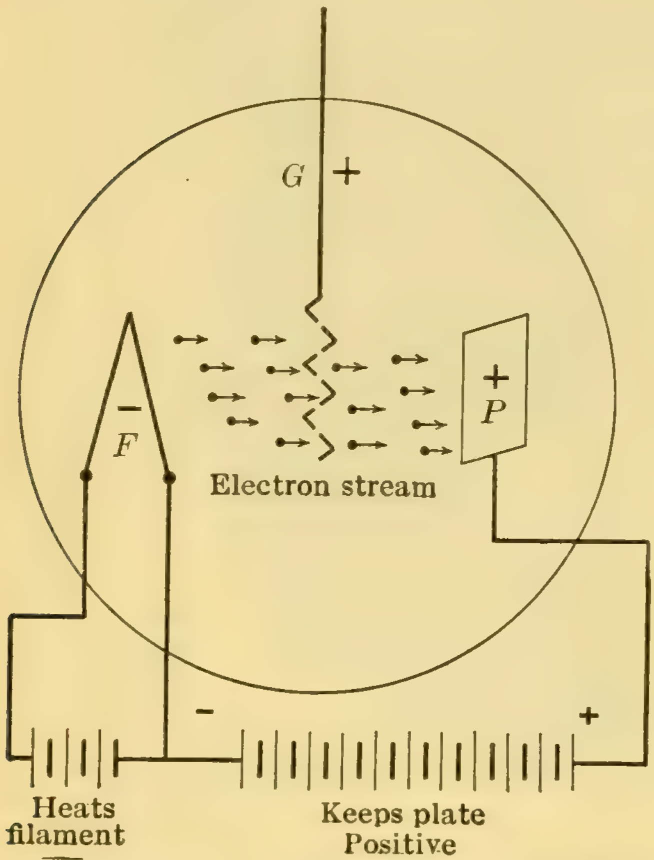


FIGURE 690.—A POSITIVE GRID INCREASES THE ELECTRON STREAM.

If the grid is made −, electrons are repelled by it back toward the filament from which they came (Figure 691). Few or no electrons, therefore, reach the plate, and the current in the plate circuit becomes smaller. If the plate battery has the proper voltage, a small + potential of the grid will cause a large current through the tube from filament to plate; a small − potential of the grid may stop the current through the bulb entirely. Thus we see that the grid is the *control element* of the tube.

Because of the action described above, the audion or three-electrode tube may act as a relay does: a small change in the voltage applied to the grid makes a large change in the current which the plate battery sends through its circuit. That is, it amplifies the signals. This is shown in the nearly vertical part of the heavy curve in Figure 692. If an alternating voltage is applied to the grid, as shown in the light wavy line at the bottom of the figure, *a fluctuating current*

in one direction (shown by the light wavy line above) will be produced in the plate circuit. This current will be reduced to zero when the grid is made sufficiently negative and will rise high when the grid is made positive. The tube thus acts like a valve. Both the relay (amplifying) action of the tube and the valve action are used in radio (§ 484). The relay action is used in long-distance telephone lines, like those across the continent.

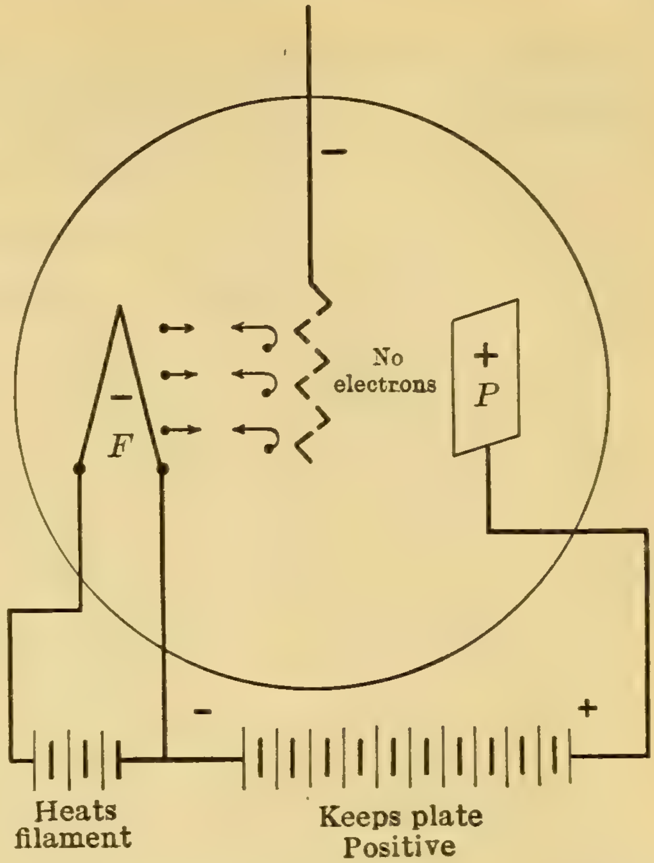


FIGURE 691. — A NEGATIVE GRID CHECKS THE ELECTRON STREAM.

A hot filament will emit more electrons than a cooler one, as shown in Figure 693. Changing the voltage of the B battery will change the current that will pass from the filament to the plate.

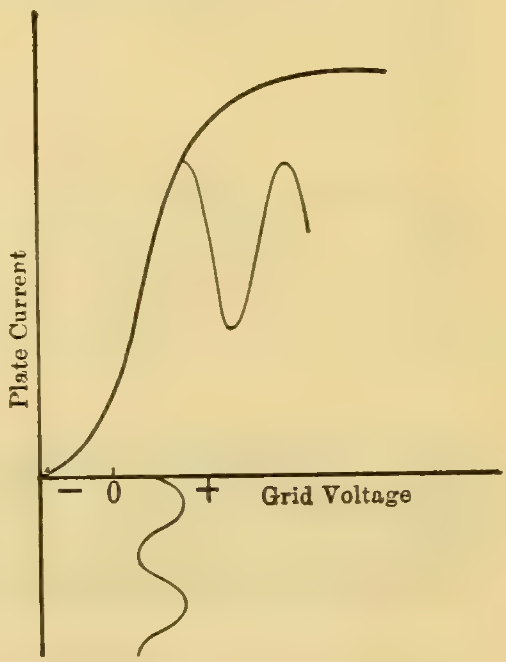


FIGURE 692. — AUDION CHARACTERISTIC CURVE.

The heavy-line curve shows the change in plate current as the grid changes from – to an increasing + charge.

476. Electromagnetic Waves. — When a Leyden jar has its coatings connected by a conductor, a flow of electrons takes place from the negative coating to the positive. Frequently a second spark may be drawn from

the same jar without recharging. This is because the inertia of the electron stream is so great that more electrons have flowed to the positive plate than are necessary to neutralize it, and it becomes somewhat negatively charged. These newly charged plates will send an electron stream in the opposite direction, and this alternate action may be repeated a number of times. This means that the discharge of a condenser is *oscillatory.* Spark discharges between the terminals of an induction coil are likewise oscillatory (Figure 694). When an oscillatory discharge takes place, the magnetic and electric fields in the surrounding space increase, decrease, and reverse, and a corresponding electromagnetic disturbance goes out into space.

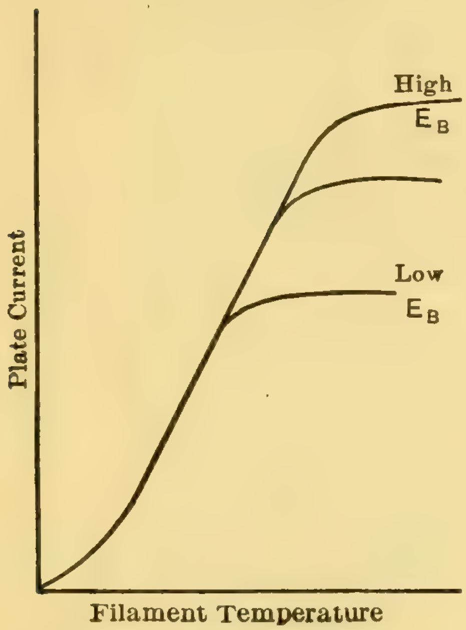


FIGURE 693. — The electron stream possible between the filament and the plate depends on the temperature of the filament and the voltage of the B-battery.

These disturbances are *electromagnetic waves.* Their nature is the same as light waves, but they are much longer. Those used in radio work range from 100 meters to 30,000

FIGURE 694. — The reflection of a spark by a rapidly rotating mirror shows many discharges back and forth.

meters in length. The speed of radio waves is probably the same as that of light waves, 186,000 miles per second, which is equivalent to 300,000,000 meters per second. As

in the case of sound, wave length is equal to velocity divided by frequency, and frequency equals velocity divided by wave length. The frequency of 100-meter waves, therefore, will be $\frac{300\,000\,000}{100}$ or 3,000,000 cycles (waves) per second. The 30,000-meter waves would have a frequency of 10,000 cycles per second. It is customary to express frequency in terms of *kilocycles:* 1 kilocycle = 1000 cycles. The frequency of the 100-meter wave would be 3000 kilocycles and that of the 30,000-meter wave, 10 kilocycles.

477. The Work of Hertz. — Although Maxwell had mathematically worked out the existence of electromagnetic waves, such as light waves, the actual existence of these waves was first demonstrated by Hertz. The waves with which he worked are much longer than light waves and are of the sort that we now employ in radio circuits.

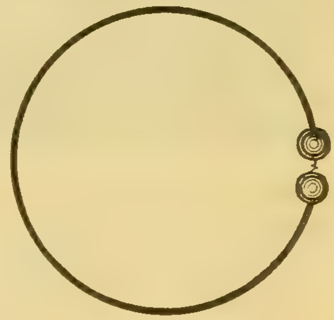


FIGURE 695.

To detect these waves, Hertz used a metal ring terminating in two small balls separated by a very small spark gap (Figure 695). When he brought this ring into the vicinity of an induction coil producing sparks, he found that every time a spark passed between the terminals of the induction coil, a small spark passed between the balls of his ring. The induction coil and the ring with its spark gap were the forerunners of our elaborate sending and receiving radio stations.

478. Electrical Resonance. — In the apparatus just described, only a minute part of the energy of the electric waves radiated by the induction coil was converted again into electric current by the ring. In a later experiment, Lodge showed how to set up an oscillating circuit. This con-

sisted of a Leyden jar, the outer coating of which was connected to one end of a loop of wire (Figure 696). The other end of the wire terminated in a ball placed very near the ball terminal of the inner coating of the Leyden jar. This loop of wire possesses self-induction (§ 321) or *inductance.*

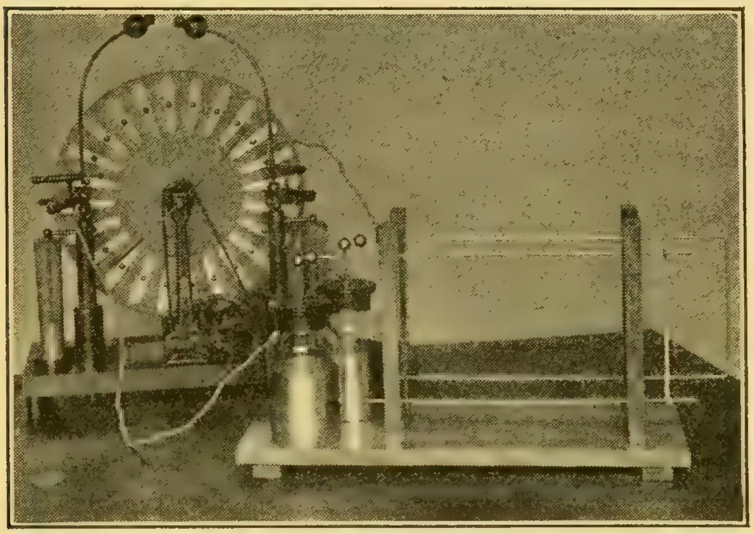


FIGURE 696. — The Leyden jar and wire loop at the rear are connected to the static machine. The front jar and loop make the receiving circuit. The wire at the right end is moved to adjust the length of the loop.

When the two coatings of the Leyden jar were connected to an induction coil, the jar and wire loop together constituted an *oscillating circuit,* and electromagnetic waves of a definite period were radiated from the spark gap. We should carefully note that the oscillating circuit consists of a condenser (the Leyden jar) connected to an inductance (the loop of wire), and is therefore a resonant circuit.

A similar jar is placed near and provided with a loop, the length of which can be varied. Near the knob of the second jar is a knob on one end of the loop, leaving a minute spark gap between the knobs. When oscillations are started in the first circuit, there is no evidence of action in the second until by experiment the wire loop is made the proper length. When this length is found, then sparks pass across the gap between the knobs. This is because the period of oscillation of the second (receiving) circuit is the same as that of the first (sending) circuit. That is, the receiving circuit is *tuned* to the sending circuit. From the

similarity of this action to that of setting a tuning fork in vibration by the waves of another fork of the same frequency (§ 162), we say that the circuits are in *electrical resonance.*

These experiments, then, illustrate the production of electromagnetic waves and their reception by a circuit *tuned in resonance* with the sending circuit. It was from these beginnings that Marconi developed his epoch-making discovery of wireless telegraphy. The progress made in the last quarter century in this great art has been in the constant improvement of detectors, and in the development of sending and receiving circuits to such great power that Hertz's range of a few feet has been increased to half the distance around the earth.

QUESTIONS

1. Explain the use of the filament and the plate in a vacuum tube.

2. State the effect of a positive grid and of a negative grid on the flow of electrons in the tube.

3. When an alternating voltage is applied to the grid, what kind of current flows in the plate circuit?

4. Explain the relay action of an audion tube.

5. Describe the character of the discharge of a condenser.

6. How are electromagnetic waves produced? Compare radio waves with light waves and X-rays, as to nature and as to wave length.

7. Describe the experiment of Hertz.

8. What are the essential parts of an oscillating circuit? What are the conditions for electrical resonance?

9. Explain what is meant by *tuning* an oscillating circuit.

479. Detectors. — The spark-gap receiving circuit described above can only be used a few feet from the sending circuit, because it requires a large amount of energy. Marconi used first a tube of metal filings (Figure 697) in

circuit with a battery and relay. The electric waves caused the filings to cohere, reducing their resistance much as the resistance of the carbon grains in a telephone transmitter is reduced when they are compressed by the diaphragm. This reduced resistance permits the battery to send enough current through the magnets of the relay to attract the armature and close the circuit of the battery and sounder (Figure 698). It was necessary constantly to tap the coherer by a vibrating hammer like that of an electric bell to separate the filings again when the waves stopped passing. The coherer has been entirely replaced by much simpler and more sensitive devices. Those most commonly used are the crystal detector and the audion tube. The latter has already been described and its use in radio will be explained later.

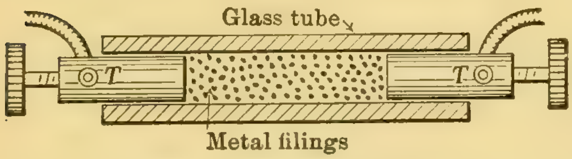


FIGURE 697. — COHERER.
TT, terminals.

480. The Telephone Receiver in Radio. — Before describing the crystal detector, those few who have not seen radio sets in operation should recall that both wireless telegraph and telephone messages are now universally heard through some form of telephone receiver. This will not permit a high-frequency current to pass through it because of its great self-induction. Further,

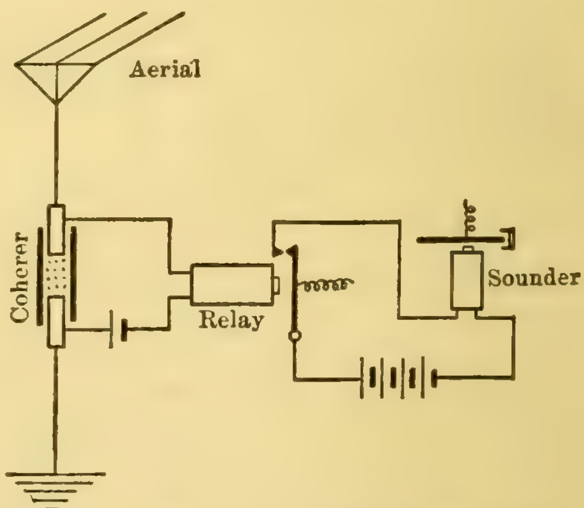


FIGURE 698. — COHERER RECEIVING CIRCUIT.
An electric bell, the hammer of which taps the coherer tube, is included in the sounder circuit, but not shown.

even if it could vibrate at the same frequency as radio waves (Figure 699, top), it would produce no audible sound, since these radio frequencies are far beyond those to which the ear is sensitive. The alternating currents set up in the receiving apparatus must be rectified, that is, changed into currents in one direction (Figure 699, middle). If these rectified impulses act in groups, and the groups succeed each other not less than a ten-thousandth of a second apart, (1) the successive small pulls of the individual impulses in one group will finally draw the diaphragm of the receiver toward the magnet (Figure 699, bottom); (2) the magnet will release the diaphragm between groups; and (3) thus vibrations will be produced that the ear can hear, since the diaphragm vibrates *once* for a *group* of waves, instead of for a single wave.

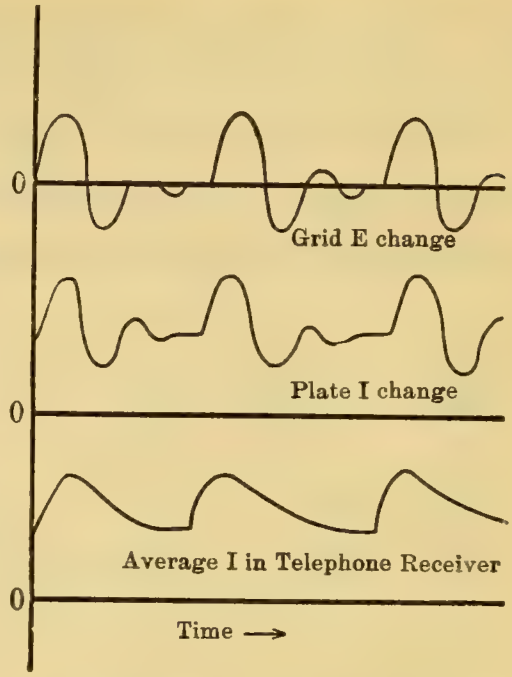


FIGURE 699.—The upper curve shows a series of alternating impulses applied to the grid; the middle curve, the corresponding current or electron stream that passes from grid to plate. The bottom curve shows that a single impulse for each group of waves reaches the telephone receiver.

FIGURE 700. — DETECTOR CRYSTAL.

481. The Crystal Detector. — It has been found that certain crystals, such as galena, silicon, carborundum, and others, conduct current much better along one axis of the crystal than in other directions. A crystal detector (Figure 700) consists of such a crystal mounted in a conducting stand in such a way that

the conducting axis of the crystal is brought into circuit. By trial, the position of the crystal that will give the greatest conduction is found. When this detector is placed in the receiving circuit, it rectifies the current produced by the incoming signals and so permits the telephone in the circuit to operate. We have already shown that the audion has a similar rectifying action.

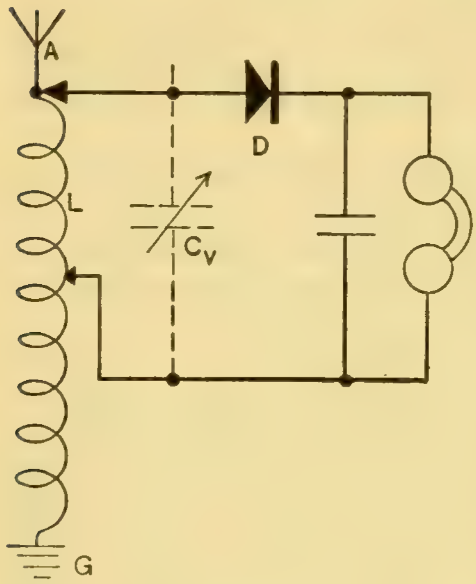


FIGURE 701.—SIMPLE CRYSTAL DETECTOR CIRCUIT.

The amount of inductance included in the circuit can be changed by sliding the lower contact along the coil.

482. A Simple Receiving Circuit. — Let us assume that a distant sending circuit is radiating electric waves. The receiving circuit will, as shown above, be an oscillating circuit consisting of an inductance and a capacity (condenser) joined in series. Joined to this oscillating circuit are a detector (D) and telephone receivers (Figure 701). The condenser of the receiving circuit is the *aërial* or *antenna* (A), consisting of one or several long wires, usually supported high above the earth by insulating supports. This forms one plate of the condenser; the earth itself forms the other plate. From one end or from the center of the aërial the *lead-in* wires are connected to an inductance, consisting of a coil of wire. The other end of this inductance coil is *grounded,* that is, connected to the earth (G), usually by means of a water pipe.

The detector and telephones are connected in shunt across the inductance (L). In order to tune the receiving circuit, the detector connections are made by sliding contacts, so that

the length of the inductance actually employed may be varied. This makes it possible to make this circuit resonate with the particular wave length that it is desired to receive. This variable inductance is called a *tuning coil.* By introducing a variable condenser (C_V) in the circuit (Figure 701), the oscillations of the circuit may be increased, and the received signals made clearer. Such a set is called a *conductively coupled,* or *single-circuit* receiving set.

483. Inductively Coupled Circuits. — The direct-coupled circuit will respond to a considerable range of wave lengths. So, if several sending stations are using nearly the same wave length, their signals will be heard more or less strongly at the same time, and confusion of receiving results. The undesired signals can be largely tuned out if an inductively coupled, or *loose-coupled* circuit is used (Figure 702). This is also called a *two-circuit* set.

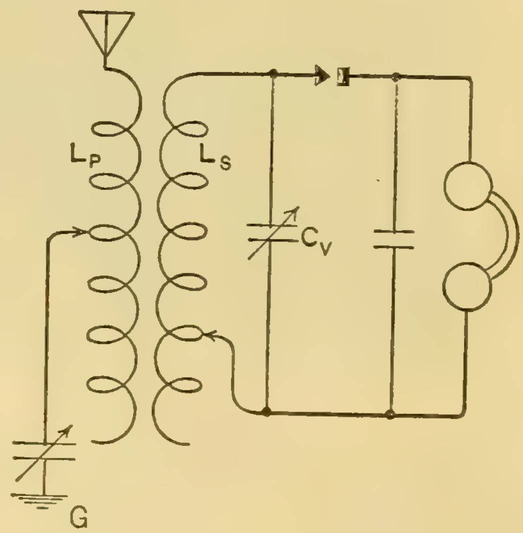


FIGURE 702. — LOOSE-COUPLED CIRCUIT.

Both primary and secondary circuits can be tuned by sliding contacts and variable condensers. The condenser at the right is the telephone condenser.

In this circuit the inductance, L_P, directly connected with the aërial, acts as a primary and induces corresponding oscillations in the secondary inductance L_S, of the detector circuit. In tuning this circuit, the capacity is changed by varying the position of the condenser plates (C_V), and the degree of coupling varied by changing the distance or the angle between the two inductances. The secondary inductance may be made to slide within the primary, as in the *loose-coupler.* The *vario-coupler* (Figure

703) consists of two coils that are independent, like those of the loose-coupler, but one turns within the other, thus changing the inductive effect.

A fixed condenser is shown across the terminals of the telephone. This is used in most circuits, as it increases the quantity of electricity flowing through the telephone and therefore increases the loudness of the signals received.

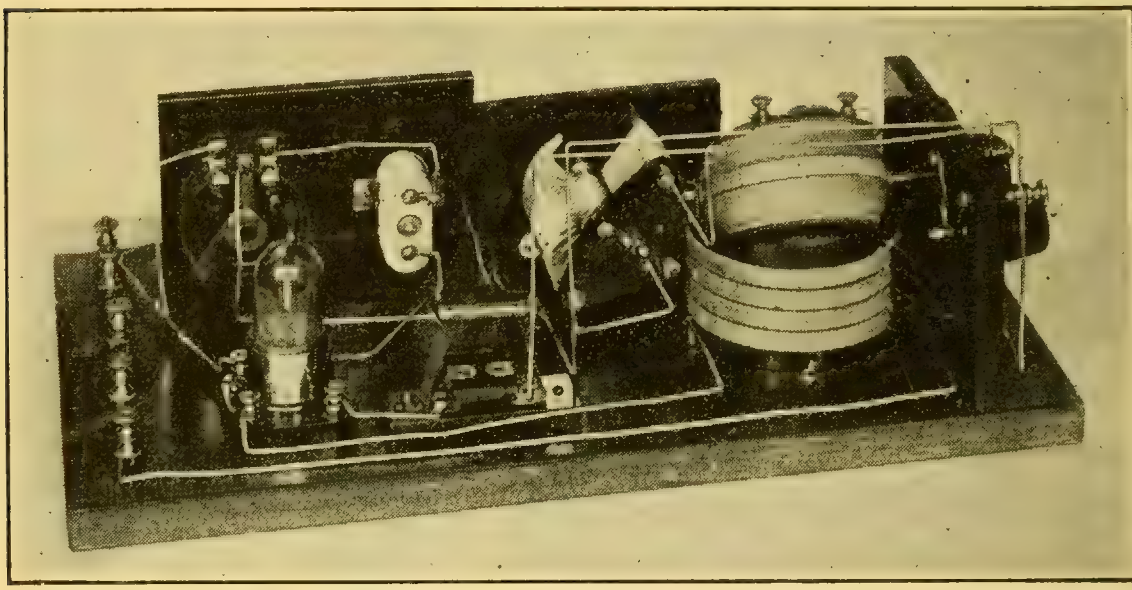


FIGURE 703. — TWO-CIRCUIT SET.

At the extreme right is the vario-coupler, the upper coil of which is turned by a knob. Next to it is a variable condenser. An audion tube is used as a detector.

484. The Audion in Receiving Circuits. — The three-electrode valve, or audion, is by far the most sensitive detector that has been used. In the simplest audion circuit (Figure 704), the grid is connected to the secondary of the tuning coil, usually through a small condenser (*GC*), and a resistance (grid leak (*GL*)) of a million ohms or more is shunted across the condenser. The audion rectifies the incoming waves, and, because of the action of the tube explained in § 475, the plate battery sends through the telephone receivers connected in its circuit currents which are much larger than

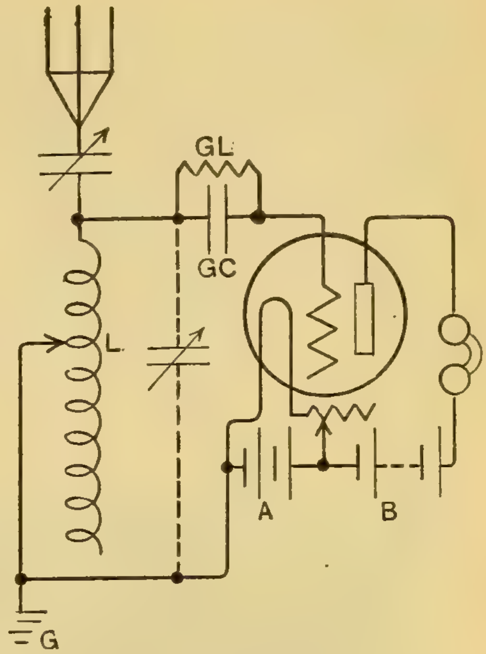


FIGURE 704. — SINGLE-CIRCUIT AUDION SET.

The set may be tuned by the variable inductance alone, or by using the variable condenser shown in the dotted lines.

those that flow in oscillating (grid) circuit. To take up all or even many of the uses of the audion in receiving circuits would carry us far beyond the range of this book. Two, however, may be briefly described: *regenerative* or *feed-back* circuits, and the use of audions as *amplifiers*.

485. Regenerative Circuit. — In this circuit (Figure 705), invented by Major Armstrong during the World War, a third inductance coil is added to the primary (L_P) and secondary (L_S) coils of the coupled receiving circuit, thus making a three-circuit set. This third coil (L_T) is connected in the plate circuit of the audion valve. The plate current, which flows through this coil and has the same frequency as the oscillating circuit of the secondary inductance connected to the grid, induces more powerful oscillations in the grid circuit, making it a "feed-back" circuit. Changes in the grid voltage produce much larger charges in the plate circuit than would take place in the two-circuit set de-

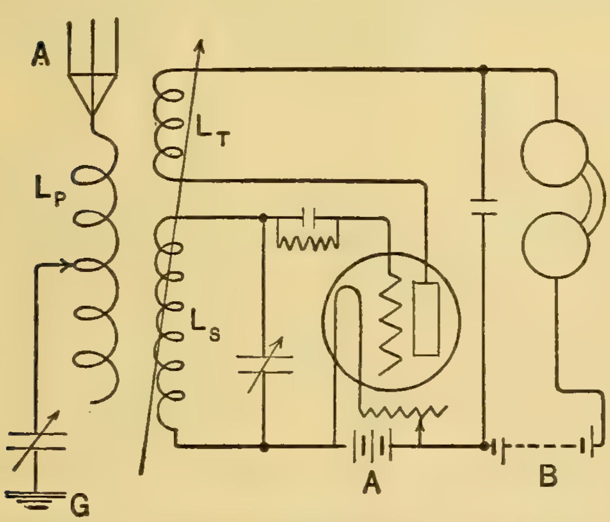


FIGURE 705. — REGENERATIVE CIRCUIT.

This differs from a simple two-circuit set in having a third inductance (L_T). The arrow indicates that the coupling of the two inductances is variable.

scribed above. This greatly increases the current flowing finally through the telephones. Thus very feeble incoming signals are made audible. Regenerative circuits may generate waves that will disturb near-by sets.

486. Audio-amplifying Circuits. — In these circuits, one or more amplifying tubes are employed. In the simplest circuit, the plate circuit of the detector tube contains no

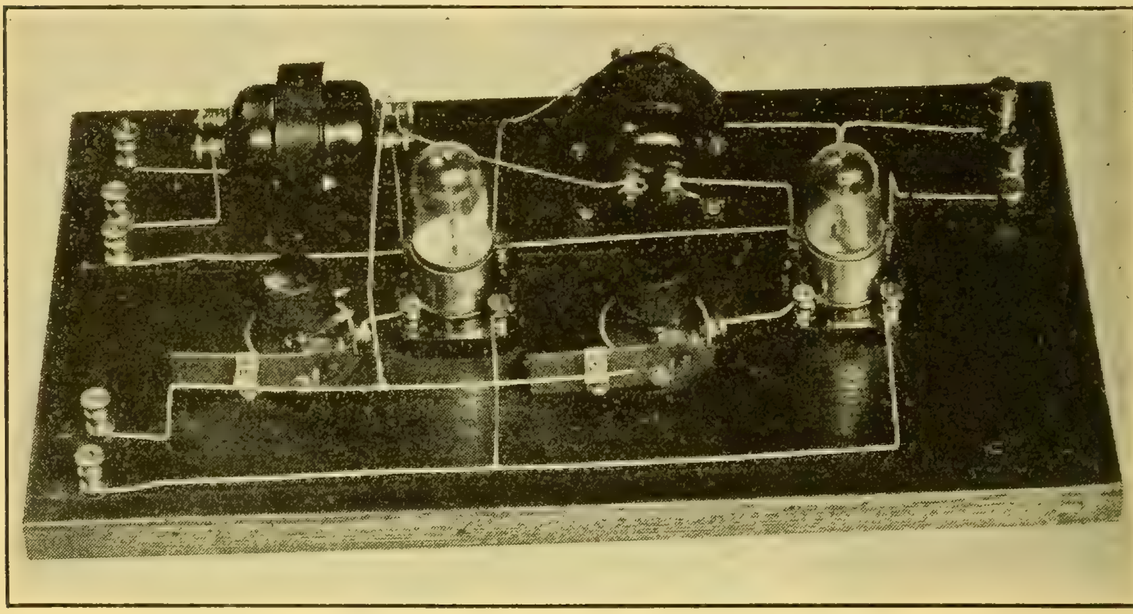


FIGURE 706. — TWO-STAGE AUDIO AMPLIFIER.
The transformers are at the rear, with the amplifying tubes and their rheostats in front.

telephone, but includes the primary of a small iron-core transformer (Figure 706). The current through this primary is much greater than the grid current, as we have shown. The transformer is a step-up one, that is, the secondary of the transformer has more turns than the primary. Therefore the voltage of the secondary is much greater than that of the primary, which is that of the plate circuit of the first or *detector* tube. This increased voltage is applied to the grid circuit of the first amplifying tube, and the current is increased again by the usual action of the tube. The plate circuit of

the amplifying tube may include the telephones, producing a *single stage* of amplification. If greater amplification is desired, the plate current of the first amplifier tube is passed through the primary of a second amplifying transformer (Figure 707). The secondary of this transformer is connected to the grid of the second amplifier tube; the plate current of this tube is commonly sent through a *loud speaker.* This is a specially designed telephone with a resonating horn.

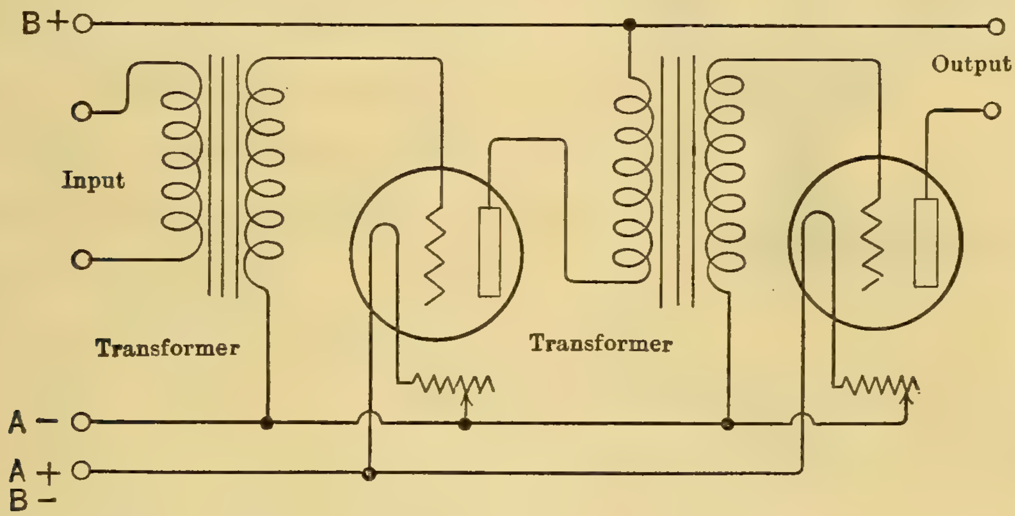
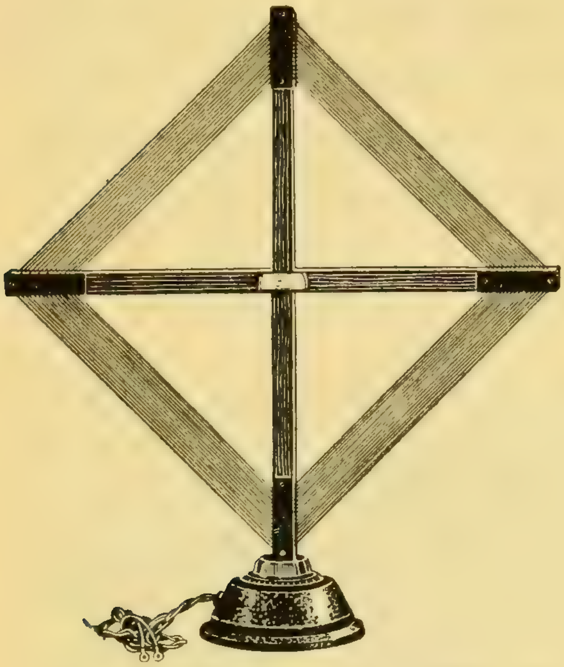


FIGURE 707.—AUDIO-AMPLIFIER CONNECTION DIAGRAM.

The plate circuit of the detector tube is connected to the *Input* posts; the loud speaker, to the *Output* posts. The batteries are connected at *A* and *B*.

487. Radio-Amplification. — Instead of amplifying the signals after they have been detected, the incoming oscillations may be amplified before entering the detecting tube. This is accomplished by impressing the incoming oscillations on the grid of a three-electrode tube. The plate circuit of this amplifier tube is connected to the grid circuit of the detecting tube. This connection is usually made through a radio-amplifying transformer, consisting of a primary and secondary coil without any iron core. Such a circuit is a *one-step amplifier.* Two or more steps of radio amplification may be secured by inserting additional amplifying tubes and trans-

formers between the first tube and the detector. It is now usual to insert a variable condenser as well as a transformer in the amplifying circuit. This permits the amplifying circuit to be tuned to the incoming wave, and is known as *tuned radio amplification.*



Courtesy of Music Master Corp.

FIGURE 708. — LOOP AËRIAL.

The strongest signals are received when the face of the loop is at right angles to the direction of the waves.

Radio sets with several stages of amplification often use a loop aërial (Figure 708) in place of an outside aërial. This makes them portable.

488. Spark Transmitting Set. — The simplest form of transmitting set consists of a circuit like that shown in Figure 710. When the key is closed, sparks pass across the spark gap between the terminals of the induction coil. These set up oscillations in the inductance-antenna circuit, whose frequency is controlled by varying the inductance. This oscillating circuit radiates electromagnetic waves into space. It will be recalled that a spark is oscillatory. That is, when the electron stream surges across the gap, not only the excess of electrons from the negative terminal pass across, but more follow from the terminal itself, leaving this positively charged. Then a smaller electric discharge takes place in the opposite direction, and this may be repeated a number

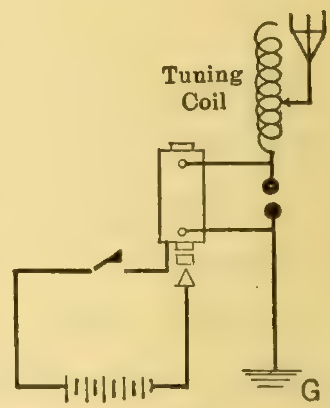


FIGURE 709. — SPARK SENDING SET.

Induction coil and spark gap are shown in the center.

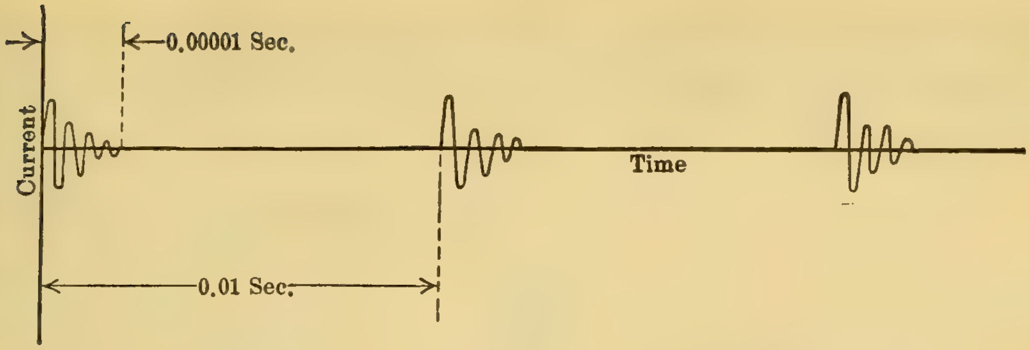


FIGURE 710. — TRAINS OF DAMPED WAVES.

These trains would cause the telephone receiver to vibrate 100 times a second.

of times, the number of electrons and the energy decreasing each time. The waves caused by such a discharge are called *damped waves* and may be represented as in Figure 710. Each spark produced, then, sets up a short train of damped waves.

A	. —	1	. — — — —
B	— . . .	2	. . — — —
C	— . — .	3	. . . — —
D	— . .	4	. . . . —
E	.	5	. . . . .
F	. . — .	6	— . . . .
G	— — .	7	— — . . .
H	. . . .	8	— — — . .
I	. .	9	— — — — .
J	. — — —	0	— — — — —
K	— . —	Period	. . . . . .
L	. — . .	Comma	. — . — . —
M	— —	Colon	— — — . . .
N	— .	Interrogation	. . — — . .
O	— — —	Bar indicating fraction	— . . — .
P	. — — .	Double dash (paragraph)	— . . . —
Q	— — . —	Distress call	. . . — — — . . .
R	. — .	General inquiry call	— . — . — — . —
S	. . .	From (de)	— . . .
T	—	Invitation to transmit (go ahead)	— . —
U	. . —	Wait	. — . . .
V	. . . —	Error	. . . .
W	. — —	Received (O.K.)	. — .
X	— . . —	End of each message (cross)	. — . — .
Y	— . — —	Transmission finished (end of work) (conclusion of correspondence)	. . . — . —
Z	— — . .		

FIGURE 711. — INTERNATIONAL CODE CHART.

Each wave train gives an impulse to the telephone receiver of the receiving circuit, through the action of the detector as already described. The result is a high-pitched hum in the receiver. By varying the time that the key of the sending station is kept closed, shorter and longer sets of wave trains are sent out and received. These are called "dots" and "dashes" respectively, and combinations of these, as shown in the accompanying chart, constitute the International Code (Figure 711).

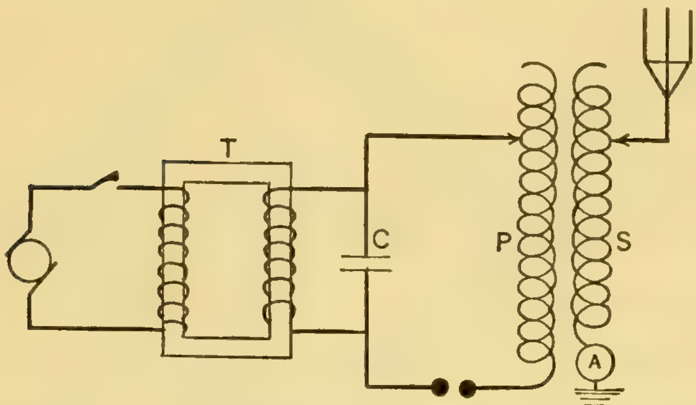


FIGURE 712. — DAMPED WAVE SENDING CIRCUIT.

When the key is closed, the circuit *C–P* oscillates, and the antenna circuit radiates damped waves.

Since it is difficult to tune out the signals of such a direct-connected spark set as that described above, such sets are not now in general use. For sending damped waves, common practice is to replace the spark coil with a high-voltage transformer, receiving its current from an A.C. dynamo. The secondary circuit of the transformer (*T*) includes a condenser (*C*) and spark gap (Figure 712), and also the primary (*P*) of the coupling or *oscillation transformer*. The secondary (*S*) of this oscillation trans-

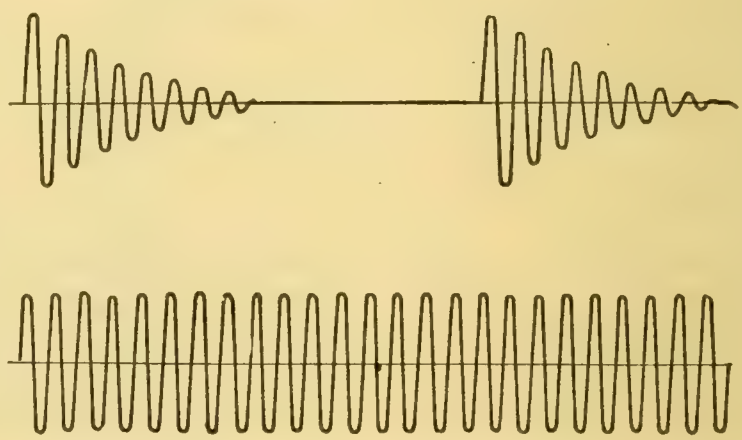


FIGURE 713. — A continuous train of undamped waves, below, is contrasted with two trains of damped waves, above.

former is in series with the antenna; that is, the sending set is coupled in the same way as the receiving sets previously described.

489. Continuous Wave Transmitting. — Various methods of radiating a continuous train of undamped waves (Figure 713) have been devised. The one most commonly used employs three electrode tubes as high-frequency generators. The circuits used are generally complicated, but their principle of action is that of the regenerative circuit described in § 485. If this circuit is properly adjusted, closing a switch in the plate circuit will cause a current to pass through the coil included in this circuit (*tickler*). This induces voltage in the coil of the grid circuit. As this grid circuit contains balanced inductance and capacity, it begins to oscillate with a definite frequency. The oscillations are increased by the regenerative action of the tickler coil and the energy necessary to maintain them is furnished by the

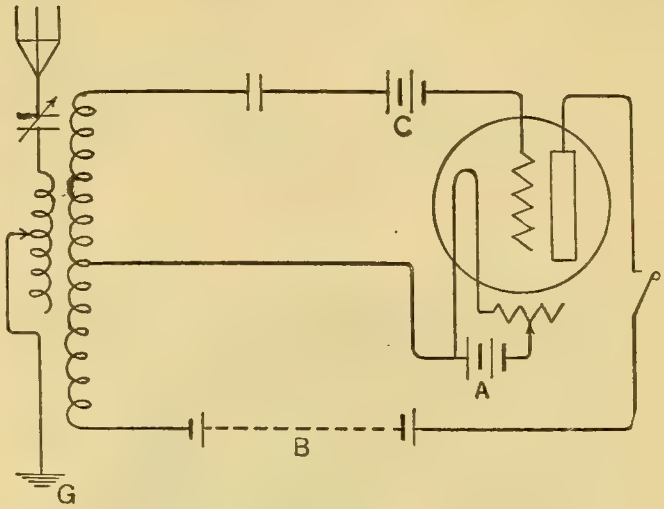


FIGURE 714. — CONTINUOUS WAVE SENDING CIRCUIT.

The tickler coil in the plate circuit starts oscillations in the grid circuit, and the antenna radiates continuous waves.

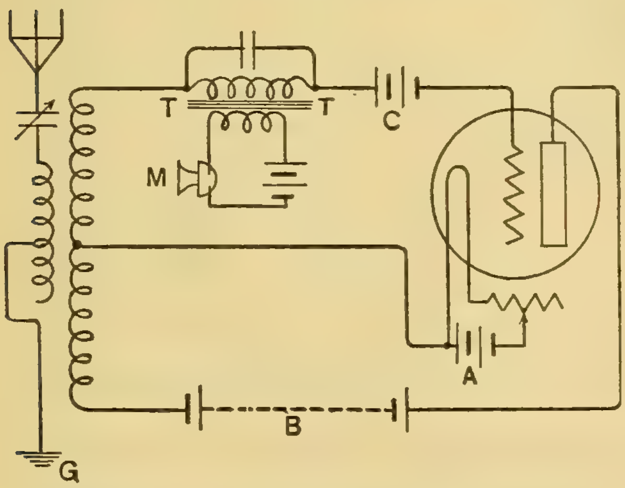
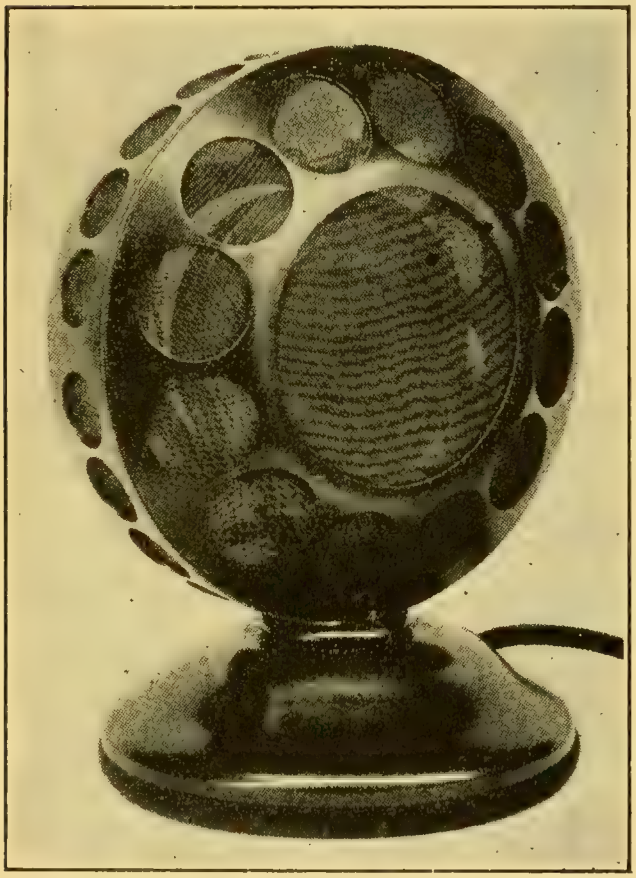


FIGURE 715. — TELEPHONE SENDING CIRCUIT.

The microphone (*M*) is connected through the transformer (*T*, *T*) to the grid circuit of a continuous wave sending set.

plate battery. If this continually oscillating circuit is coupled with the inductance of the antenna circuit (Figure 714), the set will radiate a continuous train of undamped waves as long as the set oscillates.

Undamped wave signals cannot be received by the receiving circuits that have been described, because their frequency is too great to affect the telephone. They may be broken up into groups at the receiving station by special interrupters, but this method has been replaced by an adaptation of the regenerative circuit, which employs "beats." It will be recalled that when two sets of sound waves, differing slightly in frequency, reach the ear, they will alternately reënforce and interfere with each other, and the number of pulses of sound or "beats" heard per second will equal the difference in the number of vibrations per second of the two sets of waves. Now, in the regenerative circuit, the plate circuit, as well as the grid circuit, is capable of being made an oscillating circuit. When this regenerative circuit is used for receiving undamped oscillations, the frequency of the oscillations is made, say, 1000 different from that of the incoming



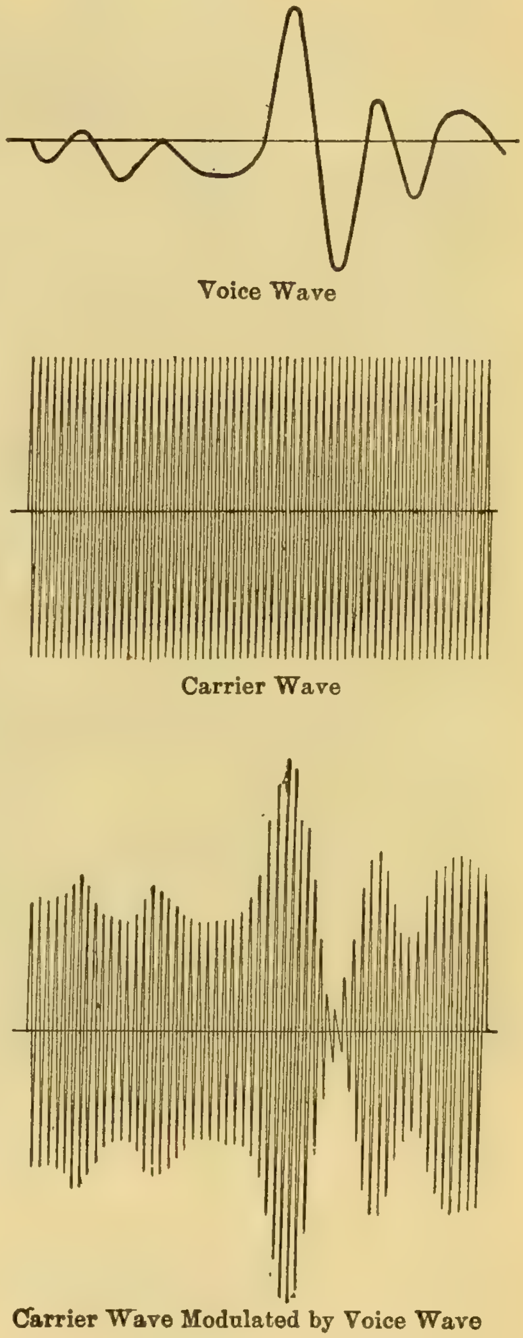
Courtesy of Western Electric Co.

FIGURE 716. — BROADCASTING MICROPHONE.

This is similar to the telephone microphone, but uses two sets of carbon grains.

signals. Under these circumstances, 1000 beats a second result in the grid circuit, and corresponding changes in the telephone current cause a musical tone of that frequency to be heard in the telephones.

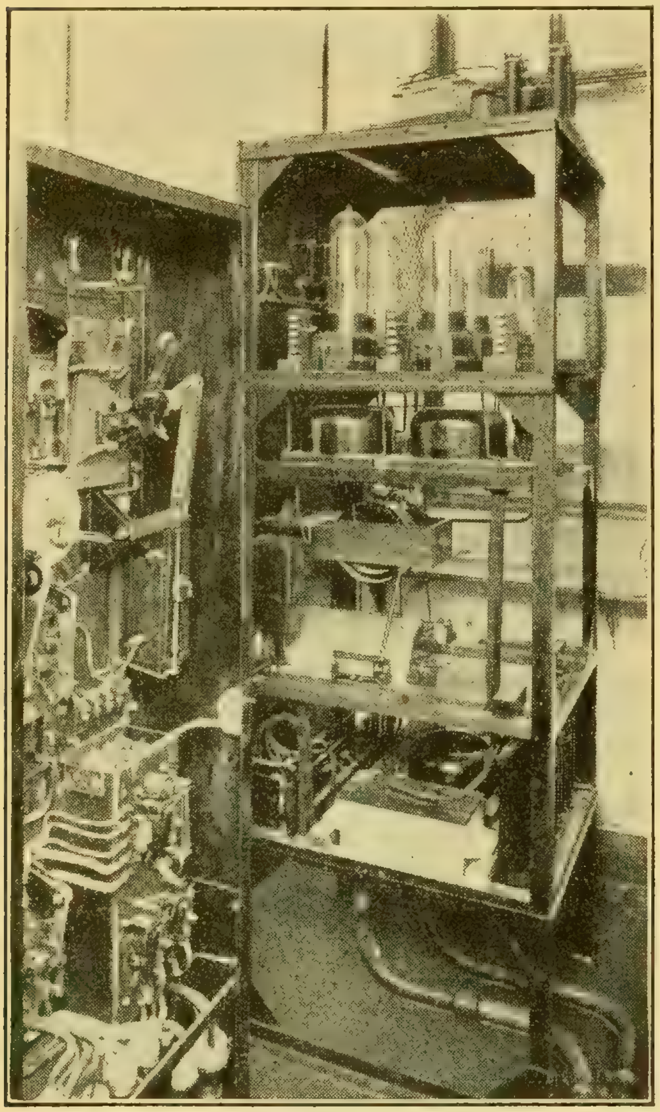
490. Wireless Telephony. — The transmission of speech by radio is made possible by an adaptation of the continuous wave system of transmission. A telephone transmitter is connected through a battery to the primary of a transformer *T*, *T* (Figure 715). The "microphone" employed as a transmitter may be a sensitive carbon grain type (Figure 716), or a two-plate condenser with a very small air gap. The secondary of the telephone transformer is included in the grid circuit of the tube. The action of the sound waves on the transmitter causes a variation in the current in the primary of the telephone transformer. This induces an alternating voltage in the grid circuit having the same frequency as the speech that caused it. The result is that the wave train sent out by the tube is "modulated," so that the waves are thrown into



Courtesy of Western Electric Co.

FIGURE 717.— The carrier wave is the continuous wave produced by the oscillating circuit. The microphone "modulates" this to the form shown at the bottom by sending the voice wave through the primary of the transformer.

groups (Figure 717). These groups of waves correspond to the current impulses that pass over the line wires in ordinary telephone conversation. Hence the antenna of a wireless telephone set radiates wave groups which, when they reach a receiving circuit, induce corresponding fluctuations in the telephone receivers of that set, and speech is reproduced. The same receiving apparatus may be used for the programs that are "broadcasted" by radio telephone as is used for radio telegraph receiving, namely, crystal sets or audion sets, either simple or regenerative. The adjustment of the latter set for "beat" reception of speech and music is now used in the "superheterodyne."



Courtesy of Western Electric Co.

FIGURE 718. — INTERIOR OF BROADCASTING SET.

The 500-watt transmitting tubes are shown in the upper part of the frame. At the left is the power panel.

QUESTIONS

1. Describe the construction and action of a coherer.

2. Why cannot a telephone be used as a detector without other apparatus?

3. Explain how the telephone diaphragm in a radio set is caused to vibrate.

4. Describe the construction of a crystal detector. What happens to radio impulses passing through it?

5. Name the parts of a simple radio receiving circuit and state the use of each.

6. Explain what is meant by an inductively coupled circuit.

7. Name two forms of coupling apparatus and state the difference between them.

8. By means of a labeled diagram, show the connection of an audion in a simple loose-coupled circuit.

9. Explain, with the aid of a diagram, the action of a regenerative circuit.

10. Describe the connection and action of an amplifier tube.

11. Of what does the oscillating circuit of a spark set consist?

12. State the difference between damped and undamped waves.

13. How are undamped waves generated?

14. How are electrical beats produced? How are they used in wireless receiving?

15. How are speech and music radiated?

SUMMARY

Air always contains some **free electrons**. Under the pressure of a high voltage, the number of these electrons will be increased, and the atoms from which the electrons have come will be left positively charged. If the positive and negative terminals of an induction coil are placed in such an **ionized gas**, the electrons and the positively charged particles will stream in opposite directions, thus constituting a current.

A Geissler tube is a partially exhausted tube with terminals sealed into the ends. In such a tube the electrons move with much greater velocity than in air. When the tube is connected to an induction coil, the gas within glows with a color and character that depend on the nature of the inclosed gas within the tube.

In **X-ray or Crookes tubes**, not more than a millionth of the air is left in the tube. When the electrons in a Crookes tube

strike the glass or an obstacle placed in their path, exceedingly short electro-magnetic waves or **X-rays** are produced.

In the Coolidge X-ray tube, the vacuum is about a billionth of an atmosphere. The cathode is a coil of tungsten wire electrically heated. The electrons are driven from this to a heavy inclined tungsten anticathode.

X-rays penetrate many opaque substances to a degree depending on the density of the substance. Their presence is revealed by causing a glow on a screen made of fluorescent material, or by their action on a photographic plate in a closed plate holder. The bones and foreign solids in the body are more opaque to the X-ray than the flesh, and so their position may be shown by the screen or photographic plate. Other uses of X-rays include examination of the teeth, treatment for cancer, and the study of the atomic structure of crystals.

A vacuum valve consists of an exhausted tube containing a lamp filament, and a metal plate having a terminal sealed into the wall of the tube. When the filament is heated by an electric current, it emits electrons; if the plate is made positive, these electrons will stream towards it, thus constituting a current.

In the DeForest three-electrode tube, a grid of metal wires, with an outside terminal, is inserted between the plate and filament.

When the grid is made positive, it **increases** the electron stream between filament and plate. **When the grid is made negative, electrons are repelled** by it back to the filament from which they came. Thus the three-electrode tube may act as a relay. **If an alternating voltage** is applied to the grid, a fluctuating current **in one direction** will be produced in the plate circuit. The tube thus acts as a **valve**, and is extensively used in radio and telephone lines.

The discharges of condensers and induction coils are oscillatory. During such a discharge, the changes in electric and magnetic fields constitute electro-magnetic waves. These waves are of the same nature as X-rays and light waves, but they are very much longer.

An oscillating system consists of a condenser and an inductance connected in series. If a second oscillating system, having the same frequency and containing a smaller spark gap, is placed in the neighborhood, sparks will pass across the gap whenever the first system is oscillating. Such a combination illustrates a case of **electrical resonance.** Wireless telegraphy and telephony depends on the production of electrical waves at the sending station and their reception by a resonant or tuned circuit at the receiving station.

Wireless detectors include the coherer, the crystal detector and electron valves. **The coherer** is a tube filled with metal filings. **The crystal detector** consists of a crystal, such as galena, mounted in a conducting stand and touched by a fine wire. This acts as a **rectifier** of the electro-magnetic waves. The rectified impulses of a received wave train are of sufficient strength to attract the diaphram of a telephone receiver.

A simple direct connected receiving circuit includes an **aërial,** connected through an **inductance** to the ground; the detector and telephones are connected in shunt across the inductance, with one of the contacts sliding. This makes it possible to **tune**, that is, adjust the frequency of the receiving circuit to that of the incoming wave, hence the variable inductance is called **a tuning coil. A variable condenser** may be shunted across the inductance. **In an inductively coupled circuit,** a second coil is placed near the inductance in the aërial circuit. If this **secondary inductance** slides within the primary, this combination is called a **loose-coupler.** In the **vario-coupler** one coil turns, but the two coils are independent. In all these cases, the alternating current produced by the waves induces a current of corresponding frequency in the secondary.

The three-electrode valves, or audion, may be used as a detector in any of the circuits described. The **grid** is connected in the secondary circuit and a battery and telephone receiver are connected between the plate and the negative terminal of the filament.

In the regenerative circuit, a third inductance mounted near

the other two, is included in the plate-telephone circuit. This acts inductively on the secondary of the coupler and greatly increases the strength of the incoming signals.

The signals may be further **amplified** by replacing the telephones by the primary of a step-up transformer. The secondary of this transformer is connected to the grid of the second (amplifier) tube. The telephones are connected in the plate circuit of the amplifier tube, or this plate circuit may include the primary of a second amplifying transformer, whose secondary is connected to the grid of a second amplifier tube. In **radio-amplification**, the incoming signals are amplified in a similar manner before reaching the detector tube.

The spark transmitting set has a transformer with a condenser across the spark gap. The transformer may be directly connected to the aërial or inductively coupled with it. The key is in the primary circuit of the transformer. Each stream of sparks causes electro-magnetic waves to be radiated from the aërial. These are damped waves, that is, the amplitude of successive waves decreases.

In continuous wave transmission, audion tubes are used as high frequency generators. A **tickler** coil similar to the third coil in the regenerative circuit is coupled with the aërial circuit. Receiving circuits for undamped waves are regenerative circuits in which the frequency of the plate circuit differs by from one to ten thousand from that of the incoming signals The **beats** produced by the difference of these two frequencies cause the diaphragm of the telephone receiver to oscillate at an audible frequency.

In wireless telephony, a telephone transmitter or a condenser with highly elastic plates separated by a very small air-gap, is inserted in the grid circuit of a continuous wave station. The result is that the wave train sent out by the tube is **modulated** so that the waves are thrown into groups, corresponding to the current impulses sent over the line wires in ordinary telephone conversation.

EXERCISES

1. What difference is there in the part played by electrons in conduction through solids, liquids, and gases?

2. Why is air considered an insulator in ordinary electrical work?

3. Why does not an induction coil spark as freely at first as it does when it has been operating some time?

4. Explain the difference between the effects produced by Geissler and by X-ray tubes.

5. What materials do X-ray operators use to protect themselves against the action of the rays and why?

6. What is the source of X-rays in a Coolidge tube? Why is the cathode in this tube heated?

7. Explain the difference between the action of a two-electrode and a three-electrode tube.

8. State the location in the circuit and the use of each battery employed in an audion receiving circuit.

9. State the similarities and differences between heat waves, X-rays, light waves, and radio waves.

10. Why can either the inductances or the condensers in a radio set be used in tuning?

11. State briefly the advantage of an inductively coupled receiving set.

12. Explain the action of the "tickler" coil.

13. Explain why amplifying tubes increase the loudness of signals received.

CHAPTER XXXVII

RADIUM

491. Discovery of Radioactivity. — The French chemist, Becquerel, happened one day to leave a uranium compound on the opaque black paper inclosing a photographic plate. When he developed the plate four weeks later, he found that the plate had been "fogged," as if it had been exposed to light. This accidental result, obtained in 1896, led to a wide range of investigations, which have resulted in the discovery of radium and the identification of many other *radioactive* substances.

Courtesy of Standard Chemical Co.

FIGURE 719. — CRYSTALLIZING RADIUM SALTS.

To produce a gram of radium bromide, 500 tons of ore, 1000 tons of coal, 10,000 tons of distilled water, and 500 tons of chemicals are needed.

492. Discovery of Radium. — Many investigators took up the search for radioactive substances. Madame Curie, the Polish wife of the Professor of Physics at the Sorbonne in Paris, made a very thorough investigation of the radioactive properties of the uranium compounds. She found that they were all radioactive, and that, strangely enough, the ore, pitchblende, from which they were

obtained, was more radioactive than any of the uranium compounds. This indicated that pitchblende contained something more radioactive than uranium. A very patient research which she and her husband undertook resulted in the discovery of several much more highly radioactive elements, of which the most important is *radium.*

493. Properties of Radioactive Atoms. — We have already seen (§ 279) that atoms consist of a nucleus containing an excess of positive electricity around which are located electrons, the number and position of these electrons depending on the atomic weight. With ordinary atoms, there is no permanent change in the number of these electrons during chemical action. The atoms of radioactive elements, however, seem to be subject to occasional explosion or sudden disintegration. Radioactive effects are the result of these explosions in the atoms, and careful study has identified the various " radiations " produced.

494. The Nature of Radioactivity. — Three different types of radiations from radioactive bodies have been recognized, and these are designated as the α (alpha), β (beta), and γ (gamma), radiations. All of these are capable of ionizing a gas, of affecting photographic plates, and of penetrating matter to varying extents. Radiations of the α type will pass through a sheet of paper. The β particles have from 10 to 100 times the penetrating power of the α rays, and the γ rays 10,000 or more times as great penetration as the α rays. The γ rays will go through a foot of solid iron or half that thickness of lead. They have been positively identified as *X-rays.* Both the deep burns to which radium workers are liable and the curative use of radium (§ 498) depend largely on the action of these tremendously penetrating

X-rays. The β rays are *electrons* discharged with tremendous speed. The α rays have been shown to be *positive ions of the element helium,* a gas inactive chemically and lighter than any other element except hydrogen. Each of these helium ions has lost two electrons and so is *positively charged.*

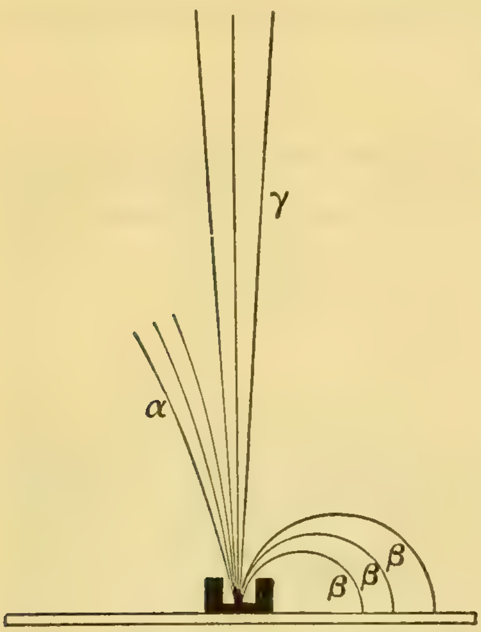


FIGURE 720. — SEPARATING THE RADIATIONS.

The magnetic field would be perpendicular to the page.

495. Method of Separating the Radiations.—The three types of radiations were separated and the determination of their character made possible by very simple means. A small quantity of a radium salt was placed in a hole in a block of lead, so that the radiations could escape only in one direction (Figure 720). A strong magnetic field was established at right angles to the direction of the radiation. The α rays were deflected slightly to one side, as if they were a stream of positive charges flowing from the radium. The identification of these as helium was made by the spectroscope. The β rays were strongly deflected in the opposite direction, as if they were negative charges. The use of an electroscope confirmed the nature of the charges of the two radiations. The γ rays were unchanged in direction by the magnetic field, shooting out straight ahead for relatively great distances, and were found to have the properties of the rays from an X-ray tube.

From the known strength of the magnetic field and the paths of the deflected rays, the electric charges, masses, and speeds of the α and β rays have been determined. The α rays

were found to travel with about $\frac{1}{15}$ the speed of light; the β rays (electrons) with from $\frac{1}{10}$ to nearly the speed of light, and the γ rays (X-rays) with the speed of light.

496. Energy in Radioactivity. — From what we have seen, we might expect that radioactive substances would constantly give off energy, and this proves to be the case. If a bit of radium is placed beside the bulb of a thermometer, it is found that the thermometer reading shows a little higher temperature than that of the surrounding atmosphere. The energy emitted by radium placed in ice would melt in less than an hour a weight of ice equal to that of the radium. Sir William Crookes invented the *spintharoscope*, to make visible the process of radioactivity. At one end of a small metal tube (Figure 721) is placed a screen covered with zinc sulphide. A short distance above this a minute particle of a radium compound is placed on a projecting wire (P). The other end of the tube contains a lens. When you look through the lens in a dark room, a tiny spark or flash of light is seen whenever an α particle strikes the screen. In the *radium clock* (Figure 722), a small quantity of radium bromide is placed in a metal tube, from which are suspended two gold leaves. The inner side of the glass tube in which the radium is suspended has two metal plates. As the gold leaves become

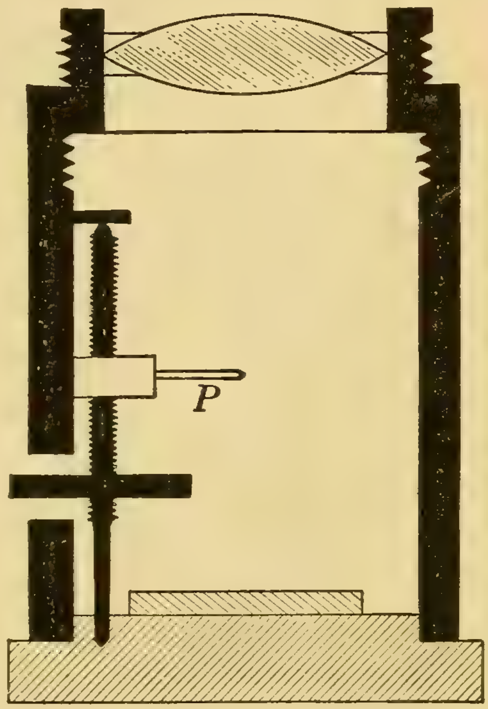


FIGURE 721. — SPINTHAROSCOPE, SECTIONAL.

Radium on the pointer P emits α rays, which produce little splashes of light when they strike the zinc sulphide screen at the bottom.

negatively charged from the radium, they diverge and strike the metal plates. They there lose their negative charges and collapse, to repeat the process again. These alternate motions of the leaves continue indefinitely. There is no apparent change in the radium compound, since it will take over 1700 years for it to lose half of its activity, that is, for half of its atoms to explode.

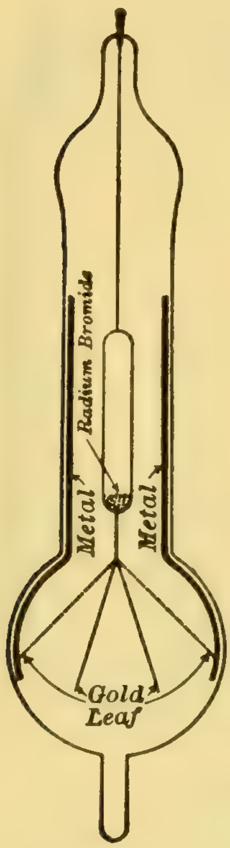


FIGURE 722.—The gold leaves diverge with the charge received from the radium and discharge when they touch the metal plates.

497. Radioactive Decay. — The facts that have been stated indicate that, since each radium atom that disintegrates loses a helium atom, the radium atom must change into an atom of another element of less atomic weight. When a quantity of a radium salt is dissolved in water, it is found that this new element, *radon* or *radium emanation,* may be collected in the form of a heavy gas of intense radioactivity. Radon loses half of its activity in about 3.85 days. Its disintegration results in the formation of a series of short-lived elements (Figure 723) of various degrees of radioactivity, and the final product is apparently lead. Radium itself is believed to be the result of several disintegrations, starting with uranium. Another series of radioactive elements is derived from thorium, one of the materials used in incandescent gas mantles.

498. Applications of Radium. — The radium discoveries have been of vast importance in experimentation and in the development of chemical and physical theory. The amount

of available radium ores is limited, the proportion of radium contained in them is extremely minute, and the extraction is a very long and difficult process. For this reason the world's supply of radium salts is very small and the cost of radium is enormous. Yet radium has found two important sets of practical uses.

If a very minute quantity of a radium salt is mixed with zinc sulphide, the disintegration of the radium causes the entire mass to glow with a faint light, as the screen of the spintharoscope does. This fact has been made use of to construct luminous figures and hands for watches and clocks (Figure 724) and other measuring instruments, and the process has been applied to other small objects to make them luminous in the dark (Figure 725).

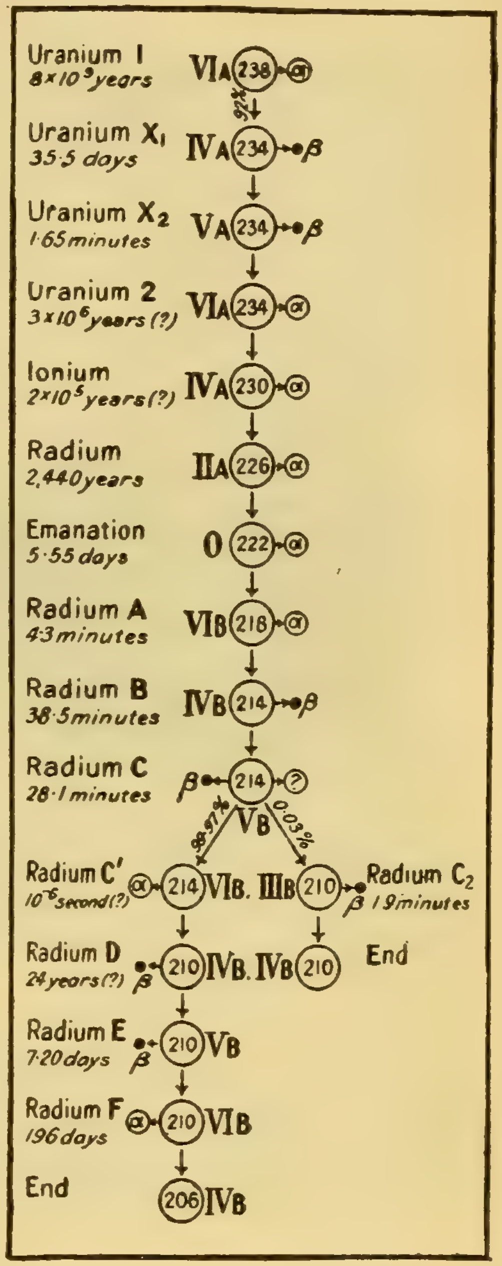


FIGURE 723.—DISINTEGRATION OF URANIUM ACCORDING TO SODDY.

Numbers in circles are atomic weights. The radiation emitted at each change is also shown.

Considerable use is being made of radium, and particularly of the emanation, for the treatment of cancer and other malignant growths. Tubes of emanation (Figure 726) or of radium salt are locally applied and then removed. When preparing these tubes, the worker protects his body by working behind a thick plate of lead and uses long-handled forceps to hold

the tubes. These tubes serve as sources of X-rays of great penetrating power, which influence the cancerous process. The emanation is particularly suited for treatment purposes, since tiny glass tubes of it can be embedded directly in the growth and left there. Since the radioactive decay of the

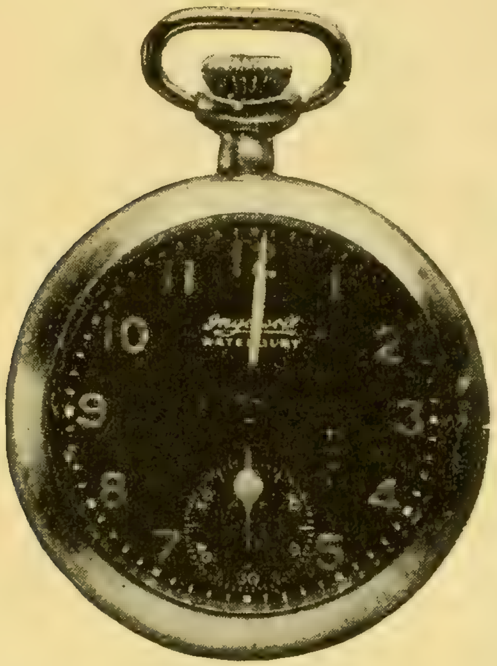


FIGURE 724. — Expensive as radium is, it is so active that a few cents' worth will make these watch hands luminous.

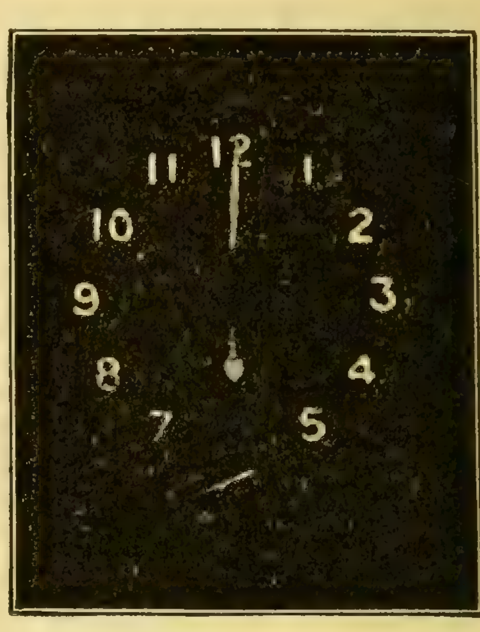


FIGURE 725. — In the dark, the figures and hands of the watch glow.

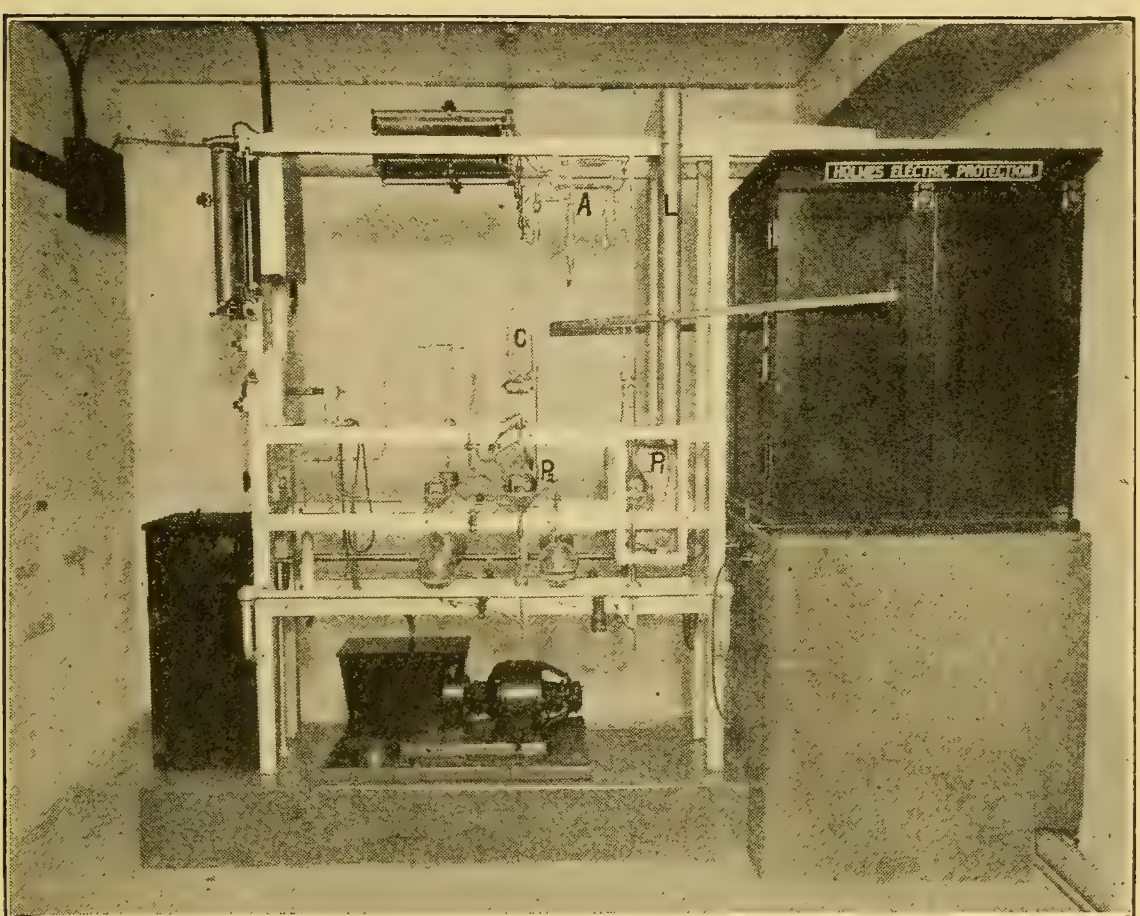
emanation is quite rapid, the radiation will end after a relatively short time, so that after the action on the tissue there will be no injurious effect on the remaining tissues.

SUMMARY

Radioactive substances, undergoing sudden disintegration of their atoms, give off **radiations**, which are capable of ionizing gases, affecting photographic plates, and penetrating matter to varying extents. Radium is the most characteristic radioactive element.

Three types of radiations are known, α, β, and γ. The γ rays have the greatest penetrating power and the α rays the least. The

α rays are **helium ions**, with a positive charge. The β rays are **electrons**, and the γ rays are **X-rays**. The three types of radiation may be separated by a strong magnetic field.



Courtesy of Dr. G. Failla.

FIGURE 726. — APPARATUS FOR PREPARING EMANATION TUBES, USED AT MEMORIAL HOSPITAL, NEW YORK CITY.

The radium is in a safe within a burglar-proof cabinet. The emanation is drawn through glass tubes inside a lead pipe (L) by a vacuum pump (P_1). P_2 draws this through purifying tubes (A) and pumps it into capillary glass tubing (C) extending along the meter stick.

A continual emission of energy accompanies the disintegration of radioactive materials. Hence radioactive materials slightly raise the temperature of their immediate surroundings.

The loss of helium converts radium into **radon or radium emanation**, a gas of lower atomic weight than radium. Radon is highly radioactive, but loses half of its activity in less than four days. Its disintegration results in the formation of a series of short-lived

radioactive elements, finally ending in lead. Another series of radioactive elements is derived from thorium.

Radioactive elements are used in the treatment of cancer and in the manufacture of luminous paints.

EXERCISES

1. State the part of Becquerel and of Madame Curie in the discovery of radium.

2. What is the chief source of radium?

3. In what respects does radium differ strikingly from ordinary elements?

4. How may a radioactive substance be recognized?

5. Distinguish the three types of radiation as to character, electric charge, and speed.

6. Explain how these radiations were separated and identified.

7. Which type of radiation is most dangerous to the experimenter and why?

8. What is the evidence that radioactive materials are constantly losing energy?

9. Describe the spintharoscope and state which type of radiation is responsible for its action.

10. Describe the radium clock and explain its action.

11. Explain what is meant by radioactive decay.

12. What is the relation between the period of a radioactive element and its degree of activity?

13. Why is radium always found in ores of uranium?

14. If a piece of gas mantle is left on a plate-holder containing a photographic plate, the pattern of the mantle appears on the plate when it is developed. Explain.

15. Account for the high cost of radium.

16. State and explain some precautions taken by experimenters with radium.

17. Explain how luminous watch dials and hands are produced.

18. Which of the radiations is utilized in cancer treatment?

CHAPTER XXXVIII

HEAT CALCULATIONS

In the preceding chapters, such topics as the heat of fusion and the heat of vaporization have been discussed at some length. It is now necessary to become acquainted with the experiments and the calculation by which these quantities were determined.

499. Method of Mixtures. — When hot and cold bodies are put together, the hot body gives off its heat to the cold one, until both are at the same temperature. If the two masses are put together under conditions such that no heat is lost to external objects, the heat lost by the hot body is entirely taken up by the cold one. This can be determined by an experiment.

Experiment 153. — In a copper or nickel can, weigh out 300 g of water about 10° below the temperature of the room. Heat an equal quantity of water to about 10° above room temperature. Stir both masses of water with a thermometer and take the temperatures accurately, and then mix the two masses of water immediately. Stir the mixture to equalize the temperature and record the resulting temperature of the mixture.

Since each gram of water loses a calorie of heat in cooling one degree, the heat lost by the warm water can be calculated by multiplying the weight of the warm water by the difference between the temperature before and after mixing. Add to the weight of the cold water one tenth the weight of the can (§ 501) that contains it, because the can has to be heated

also. Multiply this sum by the difference in temperature of the cold water before and after mixing. A comparison of these two quantities of heat will show that *the calories taken in by the cold water and the can are equal to those lost by the hot water:*

heat furnished = heat absorbed.

500. Specific Heat. — If an empty tea kettle is put on a hot stove, it does not take long to bring the iron of the kettle to the same temperature that boiling water has. A copper kettle of the same weight as the iron kettle reaches the temperature of 100° C more quickly than does the iron one. Evidently substances differ in the amount of heat necessary to bring them to a certain temperature. Is there any way that we can prove that substances differ in the amount of heat that they absorb when their temperature is raised through the same number of degrees? The following experiment with a brass weight and an equal weight of water will help to answer the question.

Experiment 154. — Add 500 grams of cold water to each of two beakers. Attach a string to a 500-gram brass weight and lower it into a narrow can into which 500 grams of water have been placed. Heat the can until the water begins to boil. The brass has the same temperature as the boiling water. Take the temperature of the cold water in the two beakers. Quickly transfer the hot weight to one of them and note the temperature to which the cold water is heated by the brass weight. To the other beaker of cold water add the 500 grams of boiling water from the can. *What is the reading of the thermometer after adding the hot water? Which absorbed the more heat in being heated from the temperature of the room to 100° C, the 500-gram brass weight or the 500 grams of water? How many calories of heat did the brass weight give to the cold water? How many calories did the 500 grams of boiling water furnish?* (These amounts of heat are not exact, since we do not take into account the heat absorbed by the materials of the beakers and the thermometers.)

The amount of heat given up by the brass weight to the cold water in the experiment is much less than the amount of heat yielded by an equal weight of water heated through the same range of temperature. Then it must take less heat to raise the temperature of a gram of brass one degree than it does to raise the temperature of a gram of water one degree. This difference in the amount of heat required to heat a gram of various substances through one degree is due to the difference in their *specific heats.* Since water requires more heat to raise one gram of it one degree than does any other liquid or solid, it is taken as the standard for specific heat. Its specific heat is 1, that is, 1 calorie of heat will raise 1 gram of water 1 degree. Other substances absorb or give out less than one calorie per gram per degree.

The specific heat of a substance is the fraction of a calorie absorbed or given out when one gram of the substance changes temperature through one degree Centigrade.

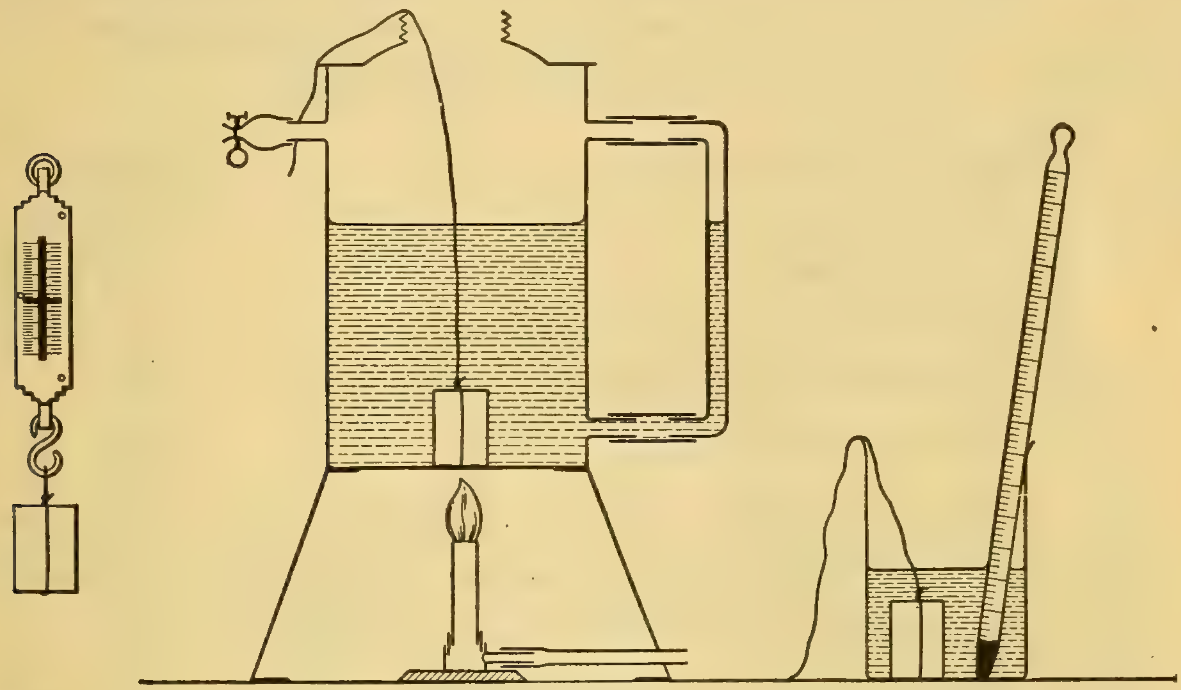
The very high specific heat of water helps us to understand why it takes so long to bring water to boiling on a stove and why the temperature of the large masses of water in lakes and oceans changes so slowly. Because of this fact, regions adjacent to large bodies of water are favored by warmer winters and cooler summers than inland regions of the same latitude.

In Table III of the Appendix, the specific heat of a number of common substances is given. Among the metals, lead has a low specific heat while zinc and copper have higher ones. Aluminum has a specific heat over twice that of iron, but in considering the use of the two metals for cooking utensils, differences in specific gravity and in their ability to absorb and radiate heat must also be taken into account.

501. Determination of Specific Heat. — The numerical value of the specific heat of a substance can be found by

obtaining exact values for the temperatures and masses in the preceding experiment. Proper precautions should be taken to prevent the heat of the room from affecting the result.

EXPERIMENT 155. — Put a 500-gram block of lead or aluminum (Figure 727, *A*) in a can of water and heat the water to the boiling point. In an insulated can, weigh out enough cold water to cover the metal



A *B* *C*

FIGURE 727.—The metal is weighed (*A*), heated to 100° (*B*), and placed in a known weight of cold water (*C*).

block when it is put in the can. When the metal is heated to the boiling point of water, take the temperature of the cold water, lift the block from the hot water into the cold, stir the cold water quickly with a thermometer, and record the resulting temperature of the mixture.

To calculate the specific heat of the metal block, the heat absorbed by the cold water is first found by multiplying the weight of the water plus one tenth of the weight of the can, by the change in temperature of the water. The number of calories thus obtained must equal the calories furnished by the hot metal, according to the previous experiment. This gives us the equation:

Weight of water × change in temperature = weight of metal × change in temperature × specific heat. From this the specific heat of the metal may be found by dividing the first member of the equation by the product of the weight × the temperature change of the metal.

502. Illustration of Method. — Let us assume a typical set of readings for the preceding experiment and use the readings to calculate the specific heat of lead.

Weight of water	300 g
Weight of can	120 g
Weight of lead	500 g
Temperature of water before mixing . .	16°
Temperature of lead before mixing . . .	100°
Temperature of mixture	20°

One tenth the weight of the can, 12 g (its mass × its specific heat), is added to 300 g of water, making the equivalent of 312 g to be warmed. Multiplying 312 g by 4° increase of temperature, we find 1248 calories absorbed by the water and can. This equals the heat furnished the lead or 500 g × 80° (decrease in temperature) × specific heat of lead. Dividing 1248 by 40,000 (500×80) gives .0312, the specific heat of lead.

503. Latent Heat of Fusion of Ice. — It has been noted in a previous chapter that a large amount of heat is required to change ice into water without raising its temperature. The quantity of heat required to change one gram of ice at 0° to water at 0° is determined by experiment.

Experiment 156. — Heat some water to a temperature of about 50° and weigh out 300 g of it in a heat-insulated can. Take the temperature of the water, and immediately drop into the water a lump of ice as large as an egg. Stir the water until the ice is melted and take the resulting temperature at once. Then weigh the mixture, to find the weight of the ice by subtraction.

To calculate the latent heat of fusion of the ice, assume these readings:

Weight of water	. . . .	300 g
Weight of can	. . . .	120 g
Weight of ice	. . . . (by subtraction)	70 g
Temperature of water	. . . .	48°
Temperature of ice	. . . .	0°
Temperature of mixture	. . . .	24.5°

The water and can give off $312 \times (48 - 24.5) = 7322$ calories. Since 70 g of ice water are warmed to 24.5° after

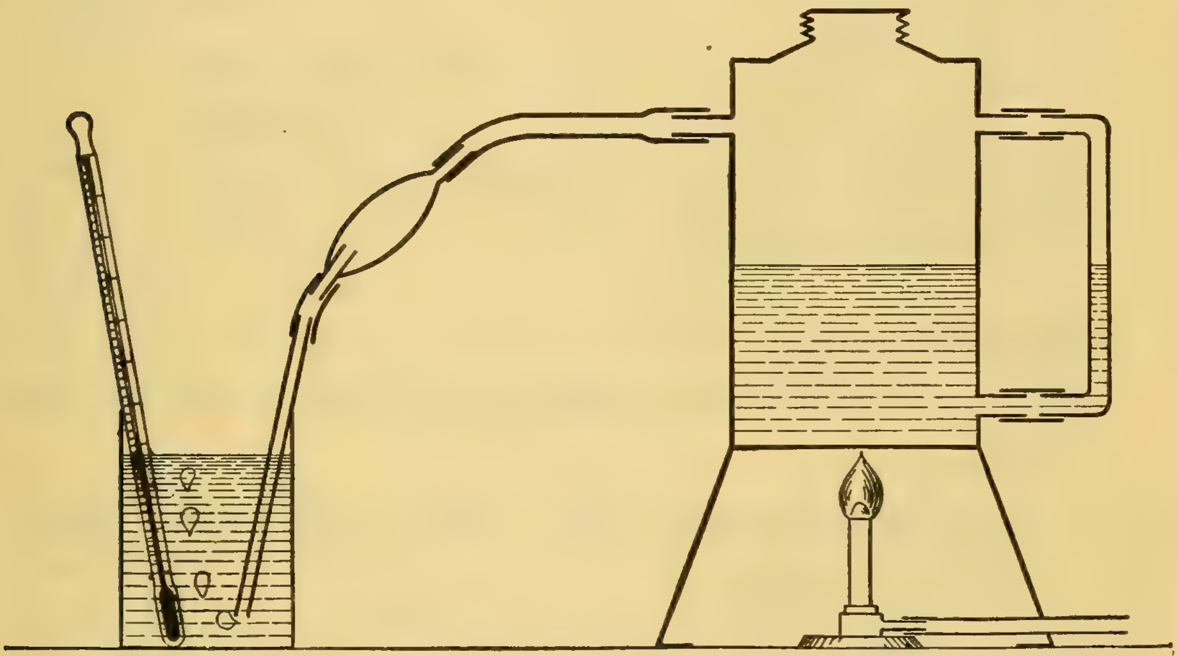


FIGURE 728. — The steam trap catches any liquid water carried over by the steam before it reaches the calorimeter.

melting, 70×24.5, or 1715 calories, are subtracted from the 7322 calories furnished, leaving 5607 calories to melt 70 g of ice, or 80.1 calories to melt 1 g of ice. The accepted value for the heat of fusion of ice is 80 calories.

504. Heat of Vaporization. — We have found that steam possesses much more heat per gram than boiling water of the same temperature. This excess heat is taken in during the

process of vaporization and is called the *heat of vaporization*. The amount of heat required to vaporize a gram of boiling water under normal pressure can be found by experiment.

EXPERIMENT 157. — Weigh out 300 g of cold water in a heat-insulated can, take the temperature, and pass steam into the cold water through a steam trap (Figure 728) until the water has been warmed considerably. Remove the steam jet, record the temperature of the water, and weigh the warmed water again so that the amount of steam condensed in the cold water may be found by subtraction.

Assume the following typical readings:

Weight of water	. . . .	300 g
Weight of can	. . . .	120 g
Weight of steam	. . . . (by subtraction)	12.5 g
Temperature of water	(before steam is added)	16°
Temperature of water	. (after steam is added)	40°
Temperature of steam	. . . .	100°

Calculation:

Can and cold water absorb $312 \times (40 - 16) = 7488$ calories.

12.5 g of steam furnish $12.5 \times (100 - 40) = 750$ calories after condensing.

$7488 - 750 = 6738$ calories furnished by condensation of 12.5 g of steam.

$6738 \div 12.5 = 539$ calories furnished by one gram of steam in condensing.

Various values have been given for the heat of vaporization, such as 536, 537, and 540, the latter probably being the most accurate.

505. Various Types of Problems. — It frequently happens that it is required to find quantities other than the specific heat, heat of fusion, or heat of vaporization. For example,

it might be required to find how much iron would cool a given amount of water 10°, or how the temperature of a quantity of water would be changed by the addition of a given weight of ice, etc. No general rules can be given for these varying forms of problems, but all of these problems resolve themselves into an equation in which the heat furnished is one member and the heat absorbed is the other. When a substance changes state, it furnishes or absorbs heat and if it is changed in temperature, it also absorbs or furnishes still more heat, which must be calculated separately.

506. Coefficient of Expansion. — It has been noted in § 86 that the various solids have unequal rates of expansion. The exact amount of expansion of various materials, such as those used in accurate instruments and in metal structures, must be known so that an allowance may be made for such expansion. *The coefficient of linear expansion is the rate of expansion per unit of length for each degree Centigrade.* It may be determined by experiment.

Experiment 158. — Materials to be tested are made up in the form of tubes about a meter long. Fasten one end of the tube rigidly and support the other end on a roller-supported shaft which moves a pointer over a circular scale. The rigidly supported end of this tube should then be connected by means of a rubber tube with a steam boiler like that used in Experiment 156. Set the pointer at 0 on the scale. Measure the length of the tube between the two supports, and the diameter of the shaft of the pointer. Pass steam through the tube until the pointer stops moving. *Through how many degrees did the pointer move? Through what fraction of a circumference was the shaft turned? What is the diameter of the shaft? Its circumference? What was the total expansion of the tube? How many degrees Centigrade above room temperature was the tube heated? How much is the expansion for 1° C?* This is the expansion of the part of the tube between the supports. *What would be the expansion of 1 cm of it for 1° rise of temperature? What is the coefficient of expansion of the material of the tube?*

Other materials may be tested in the same way and the results checked by the values given in Table III in the Appendix. The same table will be useful in solving or testing problems based on expansion.

507. Problems Involving Coefficient of Expansion. — Since the coefficient of linear expansion means the fractional increase in length of any unit during an increase of 1° C, the total linear expansion of any body may be found by multiplying length × temperature increase × coefficient of expansion. Thus, an iron rail 50 ft long, during an increase of 25° C, will expand $50 \times 25 \times 0.000012 = 0.015$ ft. If the length of a bar of iron had been 50 cm, its expansion under the same conditions would have been 0.015 cm.

A brass pendulum rod 30 in long will expand during a 15° increase in temperature $30 \times 15 \times 0.000018 = 0.0081$ in.

If an aluminum rod 100 cm long expands 0.046 cm when its temperature increases 20° C, the coefficient of expansion of aluminum is $0.046 \div (100 \times 20) = 0.000023$.

In calculating the expansion of fluids, we are concerned with the change in volume and so measure the *coefficient of cubical expansion*. While each liquid has its own coefficient of cubical expansion, *all gases have the same coefficient* of cubical expansion, which is 1/273 of the volume of the gas at 0° C for each degree rise in temperature (Charles Law).

SUMMARY

When substances at different temperatures are mixed, **the loss in heat** by one **equals** the **gain in heat** by the other.

The specific heat of a substance is the fraction of a calorie absorbed or given out when 1 gram of the substance changes through 1° C. **It is found** by mixing known weights of cold water and the

heated substance, and dividing the calories furnished by the water by the product of the weight and temperature change of the substance.

The latent heat of fusion of ice is found by putting known weights of ice and warm water together. The calories absorbed by the water after the ice melts are subtracted from those furnished by the warm water, and the difference divided by the weight of the ice.

The heat of vaporization of steam is found by passing steam into a known quantity of cold water. The calories furnished by the steam after condensing are subtracted from those absorbed by the cold water, and the difference divided by the weight of the steam condensed.

The coefficient of linear expansion of a substance is the rate of expansion of the body per unit of length per degree Centigrade. **It is found** by measuring the expansion of a convenient length of the substance during a known temperature change, and dividing the expansion by the length and the number of degrees temperature change.

EXERCISES

1. How much heat is required to raise the temperature of 1 g of water 1 degree? To raise 25 g of water 1 degree? To raise 25 g of water 10 degrees?

2. If equal weights of water at 0° and 100° are mixed without loss of heat, what will the resulting temperature be?

3. If 100 g of water at 0° are mixed with 400 g of water at 100°, what temperature will result?

4. Into 200 g of water at 40° there is poured enough ice water to lower the temperature to 16°. How much heat was given off by the warm water? How much heat was taken in by the cold water? How much cold water was added to bring about this change?

5. When 300 g of water at 65° are mixed with 180 g of water at 20°, the resulting temperature is t. Express the temperature

change of the warm water. Of the cold water. Using these expressions, find the heat lost by the warm water and gained by the cold water. Make an equation of these quantities and solve for t.

6. The specific heat of lead is 0.031. How much heat is required to heat 100 g of lead from 24° to 84°? How many degrees will 100 g of lead change in temperature when the lead takes in 62 calories?

7. A block of aluminum weighing 400 g is heated to 97.6° and then immersed in an equal weight of water at 0°. The temperature is then found to be 17.6°. How much heat has the water gained? How much heat did the aluminum lose? How much did the block of aluminum lose in cooling 1°? How much heat did one gram of aluminum lose in cooling 1°? What is the specific heat of aluminum?

8. A piece of iron weighing 350 g has a specific heat of 0.11. It is heated and immersed in 192.5 g of water at 0°. The temperature of the mixture is found to be 20°. What was the temperature of the iron before putting it in the water?

9. How much heat is required to melt 1 g of ice? To melt 50 g? To melt 50 g and raise the water formed to 25°?

10. How much water at 80° must be put with 75 g of ice at 0° in order to melt the ice without raising its temperature?

11. A lump of ice weighing 75 g is melted and the resulting ice water raised to 20° by being mixed with a certain quantity of water at 60°. How much heat was required to melt the ice? To raise the temperature after melting? How much warm water was used?

12. How much ice can be melted and the resulting water raised to 40° by being mixed with 240 g of water at 80°?

13. Forty grams of water at 100° are put with 75 g of ice at 0°. What will the result be?

14. How much heat is required to vaporize 1 g of steam? To vaporize 50 g? To raise 50 g of water from 40° to steam at 100°?

15. Ten grams of steam are condensed in a certain quantity of water at 0° and the water is raised to 100°. How much water was used?

16. Enough steam is condensed in 400 g of water at 15° to raise the temperature of the water to 65°. How much steam was condensed?

17. Find the resulting temperature when 20 g of steam are condensed in 250 g of water at 10°.

18. Boiling water and equal weights of iron, aluminum, and mercury all at 100° are put on a cake of ice. Make a rough comparison of the size of the hole melted by each. If steam had been used instead of boiling water, would the hole be larger or smaller?

19. How much ice will be melted by the condensation of 200 g of steam if the whole mass has a resulting temperature of 0°?

20. 100 g of water at 80° is placed in each of three cans. 100 g of ice is put in the first, 100 g of ice water in the second, and 100 g of mercury at 0° C in the third. In which case would you expect the highest resulting temperature? The lowest temperature?

21. Calculate the resulting temperature in each case in Problem 20.

22. Find the expansion of 1 mile of copper wire when it is warmed from 0° C to 24° C.

23. Find the coefficient of linear expansion of platinum if a wire 100 cm long expands 0.0225 cm for 25° rise in temperature.

24. An iron tire 15 ft in circumference is put on a wheel at a temperature of 200° C. How much will it shrink in cooling to 10° C?

APPENDIX

I. ESSENTIALS OF THE METRIC SYSTEM

1 meter = 10 decimeters (dm)
= 100 centimeters (cm)
= 1000 millimeters (mm)
= $\frac{1}{1000}$ kilometer
= 39.37 inches (1 in = 2.54 cm)
1 gram = weight of 1 cm^3 of water at 4° C
= $\frac{1}{1000}$ kilogram
= about $\frac{1}{28}$ ounce
1 kilogram = weight of 1 liter of water at 4° C
= 1000 g
= about 2.2 lb (1 lb = .4536 Kg)
1 liter = 1 cubic decimeter
= 1000 cm^3
= about 1.05 quart

(Except in problems where it is specifically required, it is usually unnecessary to change from English to metric units, or vice versa.)

II. IMPORTANT NUMBERS AND EQUIVALENTS

1 ft^3 water at 4° C = 62.5 lb
1 atmosphere = 14.7 lb
1 atmosphere = 76 cm mercury
1 atmosphere = 30 in mercury
1 atmosphere = 33.57 ft water
1 British Thermal Unit (1 B. T. U.) = 252 calories
Energy consumed in heating 1 lb of water 1° F (1 B. T. U.) = 778 ft-lb
1 horse power = 550 ft-lb per second = 33,000 ft-lb per minute = 746 watts = $\frac{3}{4}$ kilowatt, nearly
1 kilowatt = 1000 volt-amperes = $\frac{1000}{746}$ horse power = $\frac{4}{3}$ horse power, nearly
Heat in calories developed by resistance = 0.24 × amperes^2 × ohms × seconds = 0.24 watt-seconds

III. PROPERTIES OF MATERIALS

Substance	Specific Gravity Water = 1	Melting Point °C	Boiling Point °C	Specific Heat	Coefficient of Expansion	
					Linear	Cubical
Aluminum	2.7	658	1800	0.22	0.000023	—
Beeswax	0.96	62	—	—	—	—
Brass	8.2–8.7	1065	2100	0.089	0.000018	—
Coal	1.2–1.8	—	—	—	—	—
Copper	8.9	1083	2310	0.095	0.000017	—
Glass, crown	2.6	—	—	0.161	0.000009	0.000027
Glass, flint	3.0–3.6	—	—	0.117	0.000008	0.000025
Gold	19.3	1063	—	0.0316	0.000014	—
Iron, cast	7.0–7.7	1075–1275	—	0.119	0.000010	—
Iron, wrought	7.8–7.9	1600	—	0.115	0.000011	—
Lead	11.3	327	1525	0.031	0.000029	—
Marble	2.5–2.8	—	—	0.21	—	—
Paraffin	0.8–0.9	40–58	—	0.694	—	—
Platinum	21.37	1755	—	0.032	0.000009	0.000027

PROPERTIES OF MATERIALS — *Continued*

Substance	Specific Gravity Water = 1	Melting Point °C	Boiling Point °C	Specific Heat	Coefficient of Expansion	
					Linear	Cubical
Quartz	2.65	——	——	0.174	——	——
Silver	10.5	961	1955	0.056	0.000019	——
Steel	about 7.7	1375	——	0.118	0.000011	——
Sulphur	2.0	114.5	444.7	0.180	——	——
Tin	7.3	232	2270	0.055	0.000022	——
Zinc	7.1	419	930	0.093	0.000029	——
Alcohol, grain	0.806	−114.2	78.4	0.648	——	——
Alcohol, wood	0.812	−95	64.6	——	——	——
Carbon tetrachloride	1.58	−30	76.7	——	——	——
Ether, sulphuric	0.731	−117	34	——	——	0.0009
Glycerine	1.26	20	290	——	——	0.0005
Kerosene	0.8	——	150–300	0.5–0.6	——	——
Mercury	13.6	−38.8	357	0.033	——	0.00018
Sulphuric acid	1.84	−8.5	——	0.332	——	——

IV. SIZE AND RESISTANCE OF ANNEALED COPPER WIRE

B. & S. Gage	Diameter in Mils	Area in Circular Mils	Ohms per 1000 Ft at 20° C	Feet per Ohm at 20° C	Feet per Lb, Double Cotton Covered
10	101.89	10,381	0.997	1,003	30.9
11	90.74	8,234	1.257	795.3	38.9
12	80.81	6,530	1.586	630.7	48.8
13	71.96	5,178	1.999	500.1	61.5
14	64.08	4,107	2.521	396.6	77.4
15	57.07	3,257	3.179	314.5	97.2
16	50.82	2,583	4.009	249.4	121.9
17	45.26	2,048	5.055	197.8	153.1
18	40.30	1,624	6.374	156.9	191.5
19	35.89	1,288	8.038	124.4	246.9
20	31.96	1,021	10.14	98.66	297.9
21	28.46	810.1	12.78	78.24	374.5
22	25.35	642.4	16.12	62.05	471.7
23	22.57	509.4	20.32	49.21	584.8
24	20.10	404.0	25.63	39.02	729.8
25	17.90	320.4	32.31	31.29	901.0
26	15.94	254.1	40.75	24.54	1123
27	14.19	201.5	51.38	19.46	1389
28	12.41	159.8	64.79	15.43	1695
29	11.26	126.7	81.70	12.24	2127
30	10.02	100.5	103.0	9.707	2564
36	5.00	25.0	414.2	2.414	6666

It will be noticed that the area of #13 wire closely approximates one half that of #10, and that its resistance is twice as great. Throughout the table, an increase of three numbers corresponds to doubling the resistance, and a decrease of three numbers to halving the resistance.

V. TABLE OF RELATIVE HUMIDITY IN PER CENT

Locate the dry-bulb temperature in the column at the left marked *t*, and opposite this, in the column headed by the number of degrees difference in temperature between your wet- and dry-bulb readings, you will find the number of per cent of humidity.

t	Difference between the Dry- and Wet-Bulb Thermometers																
	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°	14°	15°	16°	
55	94	88	82	76	70	65	59	54	49	43	39	34	29	24	19	15	**55**
56	94	88	82	77	71	65	60	55	50	44	40	35	30	25	21	16	**56**
57	94	88	83	77	71	66	61	55	50	45	40	36	32	27	22	18	**57**
58	94	89	83	78	72	67	61	56	51	46	42	37	33	28	24	19	**58**
59	94	89	83	78	72	67	62	57	52	47	43	38	34	29	25	21	**59**
60	94	89	84	78	73	68	63	58	53	48	44	39	34	30	26	22	**60**
61	94	89	84	78	73	68	63	58	54	49	44	40	35	32	27	23	**61**
62	95	89	84	79	74	69	64	59	54	50	45	41	37	32	28	24	**62**
63	95	89	84	79	74	69	64	60	55	51	46	42	38	33	29	26	**63**
64	95	90	85	79	74	70	65	60	56	51	47	43	38	34	30	27	**64**
65	95	90	85	80	75	70	65	61	56	52	48	44	39	35	31	28	**65**
66	95	90	85	80	75	71	66	61	57	53	49	45	40	36	32	29	**66**
67	95	90	85	80	76	71	66	62	58	53	49	45	41	37	33	30	**67**
68	95	90	85	81	76	71	67	63	58	54	50	46	42	38	34	31	**68**
69	95	90	86	81	76	72	67	63	59	55	51	47	43	39	35	32	**69**
70	95	90	86	81	77	72	68	64	60	55	52	48	44	40	36	33	**70**
71	95	91	86	81	77	72	68	64	60	56	52	48	45	41	37	34	**71**
72	95	91	86	82	77	73	69	65	61	57	53	49	45	42	38	35	**72**
73	95	91	86	82	78	73	69	65	61	57	53	50	46	42	39	35	**73**
74	95	91	86	82	78	74	70	66	62	58	54	50	47	43	40	36	**74**
75	95	91	87	82	78	74	70	66	62	58	55	51	47	44	40	37	**75**
76	95	91	87	82	78	74	70	66	63	59	55	52	48	45	41	38	**76**
77	95	91	87	83	78	74	71	67	63	59	56	52	49	45	42	39	**77**
78	96	91	87	83	79	75	71	67	63	60	56	53	49	46	43	39	**78**
79	96	91	87	83	79	75	71	68	64	60	57	53	50	47	43	40	**79**

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